VOL. 247 JANUARY 1949 No. 1

American Journal of Science

Established in 1818 by Benjamin Silliman

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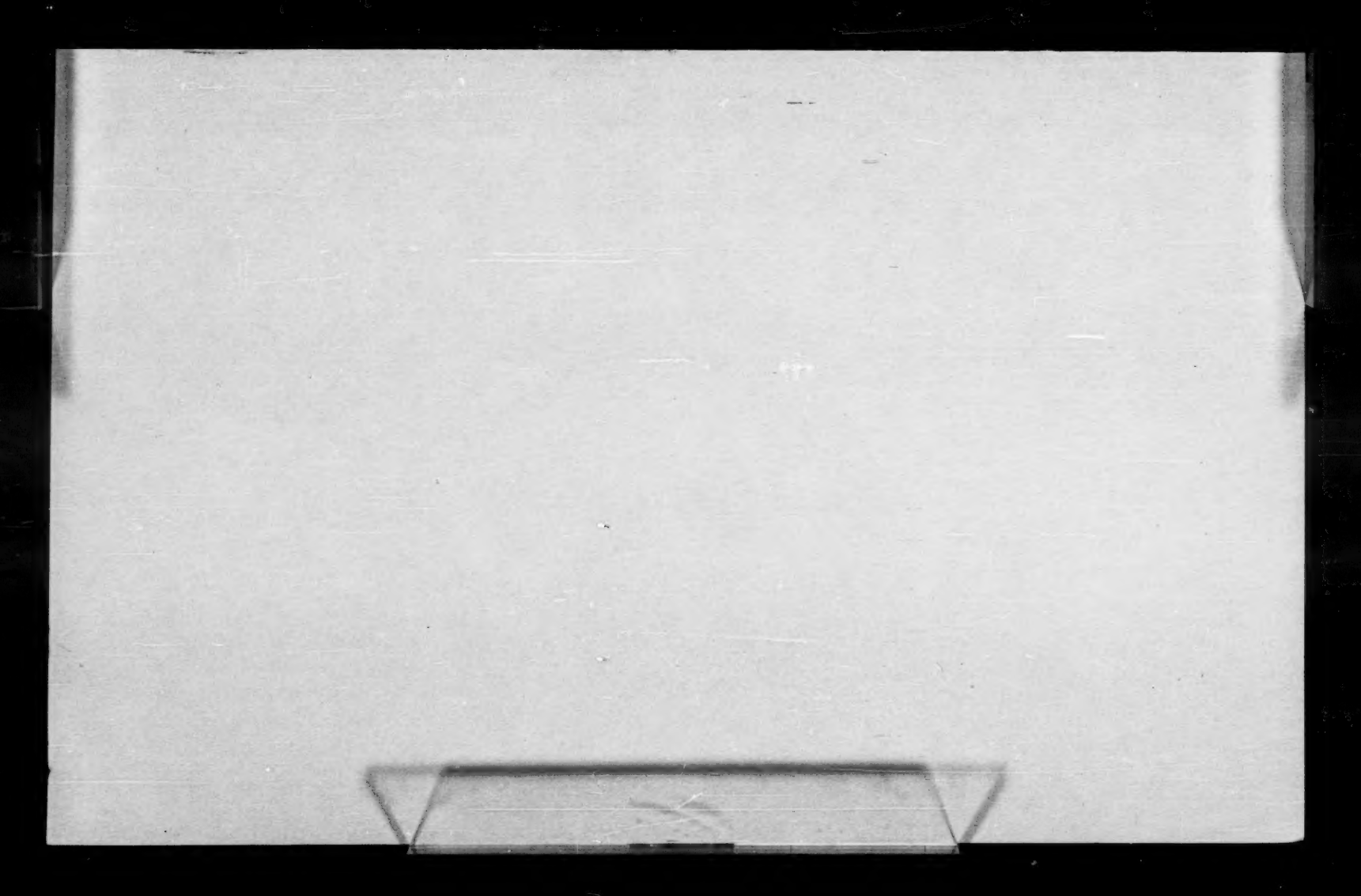
Published monthly. Eight dollars a year. Seventy-five cents a copy.
Foreign, eight dollars sixty cents. Canada, eight dollars thirty-five cents.



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USE OF THE UNIVERSAL STAGE IN SEDIMENTARY PETROGRAPHY

CHARLES M. GILBERT AND FRANCIS J. TURNER

ABSTRACT. The universal stage is of particular value in the investigation of certain sedimentary petrographic problems. Customary universal stage technique is readily applied to sedimentary petrography, but the following special applications are recommended and discussed: goniometric procedure for the determination of habit and interfacial angles in idiomorphic and sub-idiomorphic minerals, investigation of mutual relations of cementing minerals or secondary growths, determination of feldspar composition and recognition of authigenic feldspar, distinction between quartz and clear plagioclase, and identification of calcite and dolomite by optical methods.

INTRODUCTION

THE purpose of this paper is to draw the attention of sedimentary petrographers to some of the uses of the universal stage in routine petrographic examination of sedimentary rocks. As a result of their own experience, the writers believe that a universal stage is a piece of apparatus essential for a modern sedimentary laboratory and offer the following suggestions for its use.

1) One good petrographic microscope should be reserved for this work. On it a universal stage should be mounted permanently to avoid the waste of time otherwise involved in repeatedly setting up centering and adjusting the instrument prior to each investigation.

2) For all routine measurements of such properties as optic orientation, optic sign, axial angle, extinction angles, and interfacial angles, whether in uniaxial or biaxial minerals, a stage with three rotation axes (innermost vertical, north-south horizontal, and east-west horizontal) is thoroughly satisfactory. Our preference is for the three-axis stage of Silge and Kuhne, San Francisco, or the standard four-axis stage of Leitz.

3) The classic Federow procedure described in such standard German works as those of Berek (1924), Reinhard (1931) and Nikitin (1936) is recommended. Various aspects and modifications of the Federow method will be found in a number of papers written in English (Barber, 1936, pp. 221-289; Nemoto, 1938; Haff, 1941; Turner, 1940, 1942, 1947), and

in addition, a clear, concise outline of the essential procedure has been given by Haff (1942). The Federow method involves plotting all measured directions and planes on a stereographic or an equal-area projection net. In the writers' opinion this is an advantage rather than otherwise, because a clear picture of the optic and crystallographic orientation of the measured mineral develops as measurement proceeds, and any error in measurement or identification of a given direction is readily perceived and may be corrected. Moreover, use of a projection net is essential in identifying crystal faces and zones, and is the simplest method of measuring interfacial angles with a universal stage. Those unfamiliar with the use of a projection net in this connection are referred to a paper by Haff (1940) which gives a clear account of the essential procedures involved.

4) Material adapted to investigation with a universal stage includes thin sections and grain preparations permanently mounted in plastic, Canada balsam, hyrax, or some other resin.

5) The beginner is reminded that the chief advantage of the universal stage is that certain properties (e.g., axial angle, optic orientation, intercleavage angles) may be measured directly in a single crystal; whereas with an ordinary petrographic microscope such properties are usually determined by comparing optical reactions observed in a number of crystals presumed to be identical in composition. But the precision of the universal stage is still limited by the degree of accuracy with which a position of extinction or the sharpness of a cleavage surface can be estimated visually. Most measurements involve errors of the order of one or two degrees; so that the universal stage, although a convenient instrument, yields data in many cases little more precise than those determined by ordinary petrographic means.

GENERAL TECHNIQUE APPLIED TO SEDIMENTARY PETROGRAPHY

In sedimentary, just as in igneous or metamorphic petrography, the most generally useful optical data for the rapid measurement of which the universal stage is specially suited are, 1) the positions of the indicatrix axes **X**, **Y**, and **Z** in relation to visible crystallographic planes and directions and 2) the optic axial angle and optic sign. It is not within the scope of this paper to describe the Federow procedure for obtaining these data, but the use of this procedure is

invaluable in the solution of problems that commonly arise in sedimentary petrographic work.

One of the special difficulties of sedimentary petrography arises from the great variety of relatively rare minerals that are likely to be present in heavy concentrates. Such, for example, are lawsonite, diaspore, scheelite, spodumene, etc. Where only one or two grains are available for study in a single mount, optic axial angle and optic sign are properties whose determination may be essential for identification of the minerals. Also with respect to some of the more abundant minerals found in sedimentary rocks optical data obtained by means of a universal stage may be invaluable, as, for example, in the precise determination of feldspar composition (Turner, 1947), the distinction between orthorhombic and monoclinic pyroxene by the relation of Z to the prismatic cleavage, the identification of varieties of monoclinic pyroxene by means of optic axial angle, and the distinction between apatite and colorless andalusite lying on the front pinacoid {100} cleavage.

Strongly colored minerals or minerals with strong dispersion are not suited to investigation by means of a universal stage because in such minerals it is impossible to locate precisely the positions of the indicatrix axes. This applies particularly to mounted grains (as contrasted with thin sections) since the effects of dispersion and absorption are increased by the relatively great thickness of grain. Epidote minerals, dumortierite, pumpellyite, and many amphiboles belong to this category.

Universal stage procedure is also essential in those special investigations in which measurement of preferred orientation of common constituents of sedimentary rocks (notably quartz, carbonates, and micas) is desirable (Ingerson, 1944, p. 640).

DETERMINATION OF CRYSTAL HABIT AND INTERFACIAL ANGLES

So many sedimentary minerals, especially those of heavy concentrates, occur as idiomorphic or subidiomorphic crystals, that crystal habit is an important diagnostic character. Although the prevailing habit of a given mineral may usually be judged by inspection of a number of typical grains with the ordinary microscope, it is advantageous to be able to tilt individual grains about an axis within the plane of the microscope stage. This is readily done if the slide is mounted on

a universal stage. The amount of additional detailed information readily available through this simple procedure alone is significant and lends perspective to other observations made with the ordinary microscope. Such a procedure may be

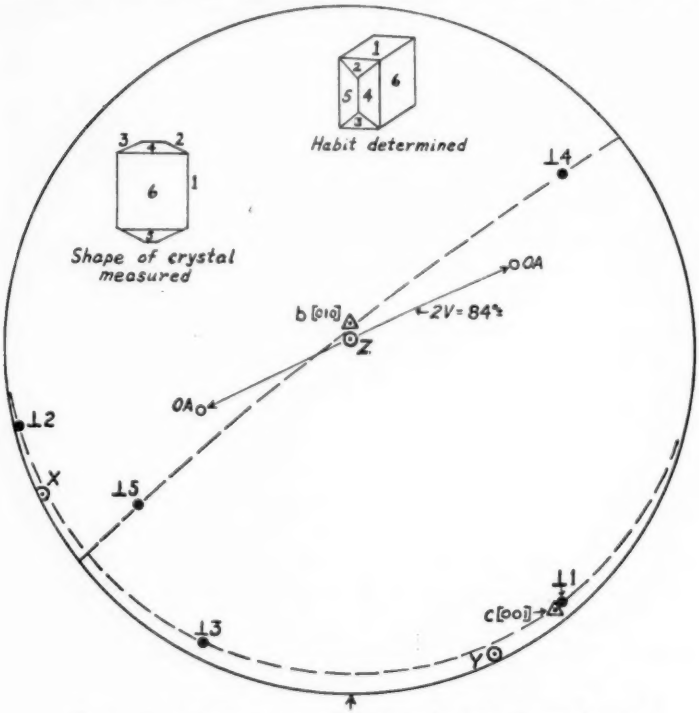

Fig. 1. Equal-area projection of heulandite (Example 1).

particularly desirable in cases where variation in habit or in mean dimensions of grains is investigated statistically in problems relating to paleogeography (Smithson, 1939, pp. 423-427; Hagerman, 1933).

Approximate determination of interfacial angles and of zonal relations of faces bounding idiomorphic crystals is another technique specially useful in sedimentary petrography, both as a step towards identifying minerals and in interpretation of rock fabrics as observed in thin sections. The position of any well developed crystal face (or cleavage plane) is readily located within one or two degrees by bringing it into

the vertical north-south or east-west plane. The interfacial angles are measured between the poles of (normals to) faces plotted on the projection net and are subject to errors of several degrees, but the data obtained are in many cases sufficiently accurate to allow certain identification of both the mineral and the measured faces. Marked differences between refractive index of the mineral and that of the mounting medium (e.g., zircon in Canada balsam) increases the error owing to total reflection at surfaces adjoining the measured face.

Example 1.—The identification of minute crystals of authigenic heulandite in an upper Miocene sandstone (Santa Margarita formation) from Santa Cruz County, California (U.C. #51-8), is cited as an illustration of the use of interfacial angles and habit in identifying sedimentary minerals. The mineral was suspected of being a zeolite because of its low birefringence (.005±) and low refractive index (mean R. I. = 1.485 ± .003), but positive identification was not possible by ordinary microscopic means.

Figure 1 shows the indicatrix and poles of measured crystal faces of a single crystal plotted on the lower hemisphere of an equal-area projection net. The measurements made with a universal stage from which these points were plotted are[1]:

	X	25 → 1
	Y	115 → 2 ↓ 45 ↑ 39
⊥	face #1	310 ← 5
⊥	face #2	13 → 1
⊥	face #3	63 → 5
⊥	face #4	40 ← 21
⊥	face #5	36 → 24

[1] For all readings given in this paper the following convention is used. The first figure is the reading on the scale for the inner vertical axis of the stage; the arrow and second figure indicate the direction and amount of downward tilt (on the N.-S. axis). To plot these on the lower hemisphere of the projection net the following rules may be followed. Turn the zero position of the transparent overlay to the measured angle (first figure) indicated on the circumference of the net; plot the point at the angle of tilt (second figure) measured in from the circumference of the net along the east-west axis in the direction indicated by the arrow. In the case of measurement of Y, the third and fourth figures in the reading are the direction and corresponding amount of tilt around the horizontal east-west axis necessary to bring an optic axis into the vertical position. The optic axes are plotted on the net, along the great circle 90 degrees from Y, in the direction and amount indicated, starting at the horizontal east-west axis of the net.

The position of Z is located graphically at 90 degrees from both X and Y.

Examination of the plotted points reveals that the poles of three faces (#1, #2, and #3) all lie on a great circle (the dashed line through these three poles), and also that this great circle passes approximately through X and Y. Thus within the limits of accuracy to be expected in such measurements, all three of these faces are co-zonal and are normal to the plane including X and Y. The corresponding zone axis (labeled b{010} in Figure 1) and the optically determined point Z should thus coincide. Also these two points are very close to the great circle which includes the poles of faces #4 and #5. The two great circles are thus mutually perpendicular within the limits of experimental error. These data suggest strongly that the mineral is either monoclinic or orthorhombic.

The general habit of the crystal can be clearly seen by tilting it into various positions, and the interfacial angles can be read from the projection net. Comparison with published data (Dana, 1899, pp. 570-610) indicates that two zeolites, mordenite and heulandite, have the habit of the mineral in question; but the interfacial angles identify it as heulandite, with the following forms developed: #1 = {001}, #2 = {201}, #3 = {$\bar{2}$01}, #4 and #5 = {1$\bar{1}$0}, and #6 = {010}. The following table gives the interfacial angles measured and, for comparison, the angles reported by Dana (shown in italics to the nearest degree).

	A ⊥ 2		A ⊥ 3		A ⊥ 4		A ⊥ 5	
⊥ 1	63	*64*	66	*66*	88	*89*	89	*89*
⊥ 2			50	*50*	34	*33*	32	*33*
⊥ 3					35	*33*	32	*33*
⊥ 4							45	*44*

Interfacial angles and the identification of faces on the single crystal illustrated in this example have been checked, with an accuracy of two or three degrees, by measurements made on many other crystals from the same concentrate. The precision of these measurements is dependent on the sharpness with which the positions of crystal faces may be estimated visually, so that the operator can decide at the time of measurement which readings are likely to be most reliable. Obvi-

ously some crystals are more favorable for such measurements than others, and in general crystals with the most clearly defined faces should be chosen. The crystal chosen for this example is particularly favorable, but because it lay on its side pinacoid {010}, face #6, other grains must be measured to identify that face positively. Such measurements prove that face #6 is indeed the side pinacoid {010} and that it is strictly normal to Z.

In minerals of very low birefringence, such as the zeolites, relatively slight changes in refractive index (possibly caused by slight variations in composition or changes in temperature) may alter the optic sign and orientation or produce large changes in the optic axial angle. Crystal habit and interfacial angles are probably much more constant than such optical data, and are therefore valuable in identification of such minerals. In the present case, for example, the optical character of the heulandite immersed in Canada balsam and heated enough to harden the balsam is very different from the optical character observed when the mineral is mounted in plastic (Castolite) hardened without heating. (The optical orientation reported in this example is for the unheated mineral.) The heating necessary to harden the Canada balsam caused the optic sign to be reversed and the positions of X and Z to be interchanged. The interfacial angles and habit of the mineral are identical in the two media.

MUTUAL RELATIONS OF CEMENTING MINERALS AND SECONDARY OUTGROWTHS

The universal stage is particularly adapted to establishing the existence of secondary outgrowths on detrital mineral grains and to bringing out the mutual relations of cement minerals and authigenic minerals in general. Contrary to what might be expected, a random section across a grain partly bounded by sharply defined crystal faces in many cases yields irregular outlines, so that the existence of crystal faces is not suspected until these have been tilted into a vertical plane. For example, in mounted light fractions of some samples of the Santa Margarita sandstone of southern Santa Cruz County, California, most of the numerous grains of feldspar appear to be angular and irregular. Yet tilting in the appropriate direction on a universal stage reveals the surprising

fact that approximately half of these grains are at least partly bounded by crystal faces, and in many grains these can be shown to be clear secondary outgrowths developed around somewhat cloudy detrital grains originally irregular.

During the examination of thin sections of some Eocene reservoir sands from the Kettleman Hills-Coalinga area, California, the writers found that, in general, quartz and feldspar grains appear to be irregularly bounded where they project into or adjoin cavities. Here, too, appropriate tilting of these free edges, even through ten or fifteen degrees, reveals the presence of sharp secondarily developed crystal faces that would otherwise remain undetected. By measuring and plotting several such faces and one or more optical directions in any grain, it is commonly possibly to identify the individual faces and so to obtain a picture of the exact crystal form that tends to develop by secondary enlargement of the detrital grains. Moreover, it may be possible to obtain reliable information as to the order of development of outgrowths and cementing minerals during lithification of the sediments in question (Gilbert, 1948). Several instances are cited below as examples of this technique.

Example 2.—This illustration of the identification of crystal forms developed on a secondary outgrowth of quartz is taken from the Eocene McAdams sand of the Kettleman Hills area, California (U.C. #S3/3C). Figure 2 shows the optic axis and poles of faces measured on a secondarily enlarged quartz grain. In the inset sketch representing the general form of the grain measured (Q_1), stippled areas are detrital quartz and diagonal lines indicate secondary outgrowths on several detrital grains; cross-hatched areas are detrital feldspar. The sketch is highly idealized to indicate the number and relative positions of the faces on several outgrowths, but it should be understood that at any one tilt of the stage only one or two of these faces are clear. With no tilt at all, faces #1 and #4 alone are distinct.

With the universal stage the positions of the optic axis (c axis) and the pole of each suspected crystal face are measured in the usual manner and with the following results:

Optic Axis	39 ← 20	⊥ face #4	350 → 3
⊥ face #1	348 → 4	⊥ face #5	28 → 32
⊥ face #2	260 ← 20	⊥ face #6	258 ← 19
⊥ face #3	315 → 16	⊥ face #7	317 → 14

Each of these readings is plotted on the lower hemisphere of an equal-area (or stereographic) projection net, and the angle between the optic axis and the pole of each face is read from

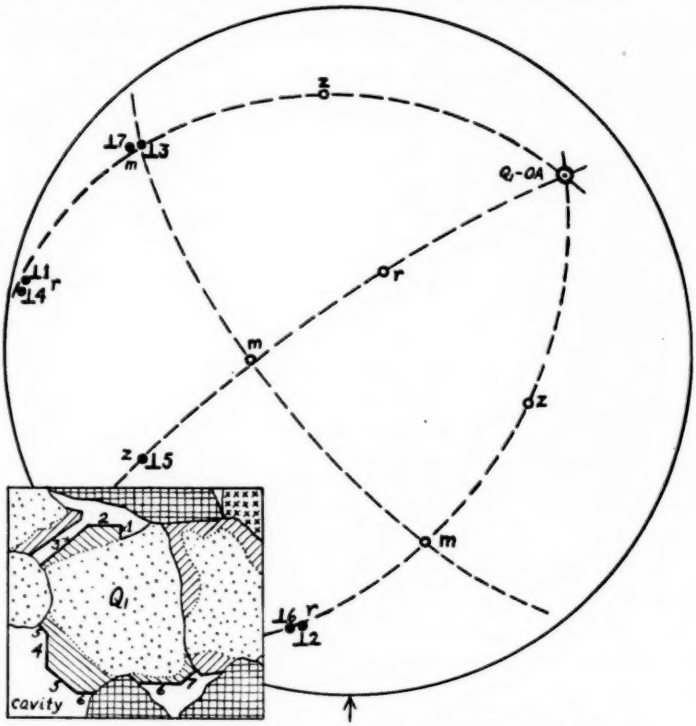

Fig. 2. Equal-area projection of quartz (Example 2).

the net. These angles are then compared with published angles for quartz to give a tentative identification of the various faces, as follows:

	Δ Optic axis	Suggested form	Correct angle (to nearest degree)
⊥ face #1	56°	r {10$\bar{1}$1} or z {01$\bar{1}$1}	52°
⊥ face #2	56°	r {10$\bar{1}$1} or z {01$\bar{1}$1}	52°
⊥ face #3	90°	m {10$\bar{1}$0}	90°
⊥ face #4	53°	r {10$\bar{1}$1} or z {01$\bar{1}$1}	52°
⊥ face #5	54°	r {10$\bar{1}$1} or z {01$\bar{1}$1}	52°
⊥ face #6	54°	r {10$\bar{1}$1} or z {01$\bar{1}$1}	52°
⊥ face #7	92°	m {10$\bar{1}$0}	90°

These results and an inspection of the points plotted on the projection suggest that among the seven faces three forms are represented; namely #3, #7 = {10$\bar{1}$0}; #1, #4 and #2, #6 = {10$\bar{1}$1}; #5 = {01$\bar{1}$1}. Alternatively #1, #4 and #2, #6 could be identified with {01$\bar{1}$1} and #5 with {10$\bar{1}$1}. The above identification can be checked by two independent means, 1) the zone relationships of faces and 2) interfacial angles.

Zone relations: The poles of all prism faces must lie on a great circle (zone) 90 degrees from the optic axis. This great circle is drawn on Figure 2 and includes face #3 while face #7 is only slightly off the zone. Assuming that face #3 is the common unit prism {10$\bar{1}$0}, the poles of the other unit prism faces can be located on the same great circle by measuring 60 degrees on either side of face #3 and are shown as open circles labeled m. Now if the other faces are indeed unit rhombohedrons, each must be co-zonal with one of the prism faces and the optic axis. This condition is satisfied in this case as shown by the diagram where each of the faces in question lies on or very near one of these great circles. For reference, the poles of the other three faces of positive and negative unit rhombohedron forms are shown by open circles labeled r and z.

Interfacial angles: The angle between each pair of faces is measured from the projection net and compared with the correct interfacial angles for the forms identified. The results are as follows, where the correct angle is given in italics:

	A 2 (r)	A 3 (m)	A 4 (r)	A 5 (z)	A 6 (r)	A 7 (m)
1 (r)	89 *86*	34 *38*	2 *0*	47 *46*	89 *86*	32 *38*
2 (r)		65 *67*	89 *86*	48 *46*	2 *0*	66 *67*
3 (m)			36 *38*	67 *67*	67 *67*	2 *0*
4 (r)				47 *46*	87 *86*	34 *38*
5 (z)					46 *46*	66 *67*
6 (r)						68 *67*

Within the limits of accuracy obtainable with the universal stage, the angles check and the faces can be considered as satisfactorily identified.

Because the angles between optic axis and each of the various faces are independent of the interfacial angles, and both are independent of the zone relations, identifications checked by all three methods can be considered certain. Where only

two or three faces occur on a crystal the identification is possible in the same manner although it may be less convincing than with a larger number; but if a single face is present the only character available is the angle between the optic axis and the face, in which case identification is considered tentative or inconclusive.

It should also be apparent that the identification of crystal faces in this manner refers to crystal forms only and not to individual faces. Thus the positive (r) and negative (z) unit rhombohedrons in quartz cannot be distinguished. The writers follow the convention that if only one unit rhombohedron form is present it is called the positive one (r); if both are present either may be called positive (r) and the other negative (z).

Example 3.—The relationship between calcite and secondary quartz outgrowths in the Eocene McAdams sand of the Kettleman Hills area (U.C. #S3/7C) is illustrated by Figure 3. The inset sketch is highly idealized and illustrates a portion of a thin section showing a triangle of calcite (C) surrounded by a detrital quartz (stippled) with secondary outgrowths (diagonal lines). The cross-hatched areas are feldspar. The optic axes of two quartz grains (Q_1 and Q_2) and of calcite (C), together with the poles of faces #1, #2, #3 and the pole of a calcite cleavage, were located in the usual manner with the universal stage and plotted on the lower hemisphere of the equal-area projection net. The readings made with the stage were as follows:

Calcite optic axis	200 ← 56	⊥ face #1	196 ← 26
$Quartz_1$ optic axis	254 ← 24	⊥ face #2	126 ← 34
$Quartz_2$ optic axis	195 ← 65	⊥ face #3	339 → 18
Calcite cleavage	182 ← 14		

The angle between the optic axis of calcite and the pole of the calcite cleavage as measured from the projection net is 43 degrees. Since this angle agrees as well as can be expected with the correct angle ($44\frac{1}{2}°$) between the c axis and rhombohedral cleavage of calcite, it can be assumed that the fracture plane measured is indeed the rhombohedral cleavage $\{10\bar{1}1\}$. With the pole of this cleavage and the optic axis (c axis) plotted on the projection, the positions of the other common rhombohedron faces of calcite can be located and are shown by open triangles labeled r ($\{10\bar{1}1\}$) and e ($\{01\bar{1}2\}$). None of these approximates the positions occupied by the poles of

faces #1 and #2, so that clearly neither of these faces is a common rhombohedron of calcite.

The angles between the optic axis of quartz$_1$ and the poles of faces #1 and #3 are 52 degrees and 89 degrees respectively,

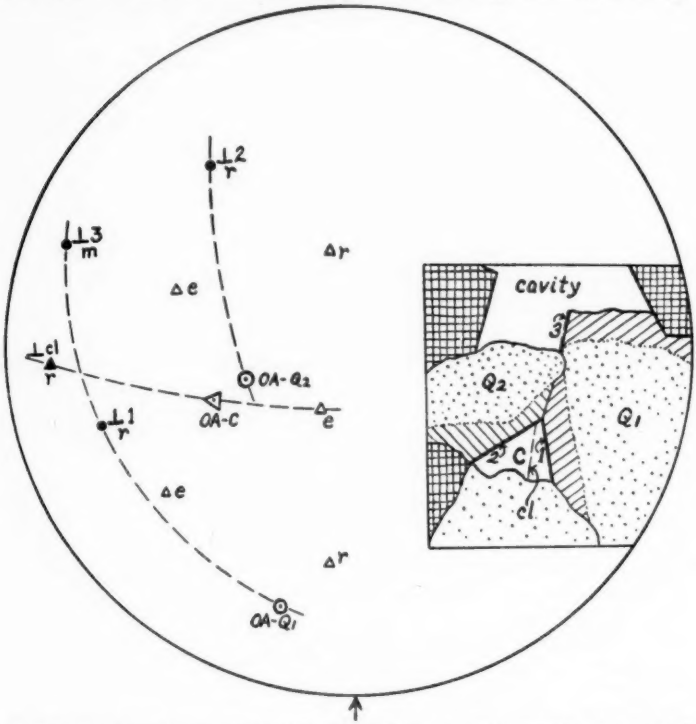

Fig. 3. Equal-area projection of calcite, C, and quartz, Q_1 and Q_2 (Example 3).

which agree with the correct angles for the unit rhombohedron r ($\{10\bar{1}1\}$) and unit prism, m ($\{10\bar{1}0\}$) of quartz. Also these two faces are co-zonal with the optic axis (c axis). Thus face #1 is determined as the rhombohedron of quartz$_1$ and is not a rational face of calcite. The optic axis of quartz$_2$ is inclined to the pole of face #2 at an angle of 51 degrees, a value that agrees with identification of face #2 as the unit rhombohedron, r $\{10\bar{1}1\}$, of quartz$_2$. This determination appears reasonable but is not positive since only one face is to be found on quartz$_2$ and zonal relations and interfacial angles cannot be used as a check on the identification.

It is concluded that faces #1 and #2 are unit rhombohedrons on quartz outgrowths, Q_1 and Q_2 respectively, and are not rational faces of calcite as at first they would appear to be. Therefore, the calcite must have crystallized later than the quartz outgrowths and has filled a void bounded by previously developed faces of secondary quartz. This conclusion is borne out by similar observations made throughout this and other thin sections from the same formation. The same technique can be used to investigate the boundary between two different quartz outgrowths, such as the one shown in the inset sketch of Figure 3. Such boundaries generally approximate to plane surfaces; but results obtained by the writers indicate that most of them are not rational faces of either grain of quartz. This was the result in the case illustrated here and probably indicates that the two quartz outgrowths developed simultaneously.

Reference data.—For convenient reference the following crystallographic angles of quartz and calcite are given to the nearest degree.

TABLE I

Common crystallographic angles of quartz

c	axis	∧ ⊥m	(10$\bar{1}$0)	90°
c	axis	∧ ⊥r	(10$\bar{1}$1)	52°
c	axis	∧ ⊥z	(01$\bar{1}$1)	52°
⊥m	(10$\bar{1}$0)	∧ ⊥r	(10$\bar{1}$1)	38°
⊥m	(01$\bar{1}$0)	∧ ⊥z	(01$\bar{1}$1)	38°
⊥m	(01$\bar{1}$0)	∧ ⊥r	(10$\bar{1}$1)	67°
⊥m	(10$\bar{1}$0)	∧ ⊥z	(01$\bar{1}$1)	67°
⊥r	(10$\bar{1}$1)	∧ ⊥r	($\bar{1}$101)	86°
⊥z	(01$\bar{1}$1)	∧ ⊥z	(1$\bar{1}$01)	86°
⊥r	(10$\bar{1}$1)	∧ ⊥z	(01$\bar{1}$1)	46°

TABLE II

Angles to rhombohedron faces of calcite

c	axis	∧ ⊥r	(10$\bar{1}$1)	45°
c	axis	∧ ⊥e	(01$\bar{1}$2)	26°
⊥r	(10$\bar{1}$1)	∧ ⊥r	($\bar{1}$101)	75°
⊥e	(01$\bar{1}$2)	∧ ⊥e	($\bar{1}$012)	45°
⊥r	(10$\bar{1}$1)	∧ ⊥e	($\bar{1}$012)	71°
⊥r	(10$\bar{1}$1)	∧ ⊥e	(01$\bar{1}$2)	38°

DETERMINATION OF COMPOSITION OF FELDSPAR

For methods of determining the composition of twinned grains of feldspar as seen in thin sections the reader is referred to Nikitin (1936) and Turner (1947).

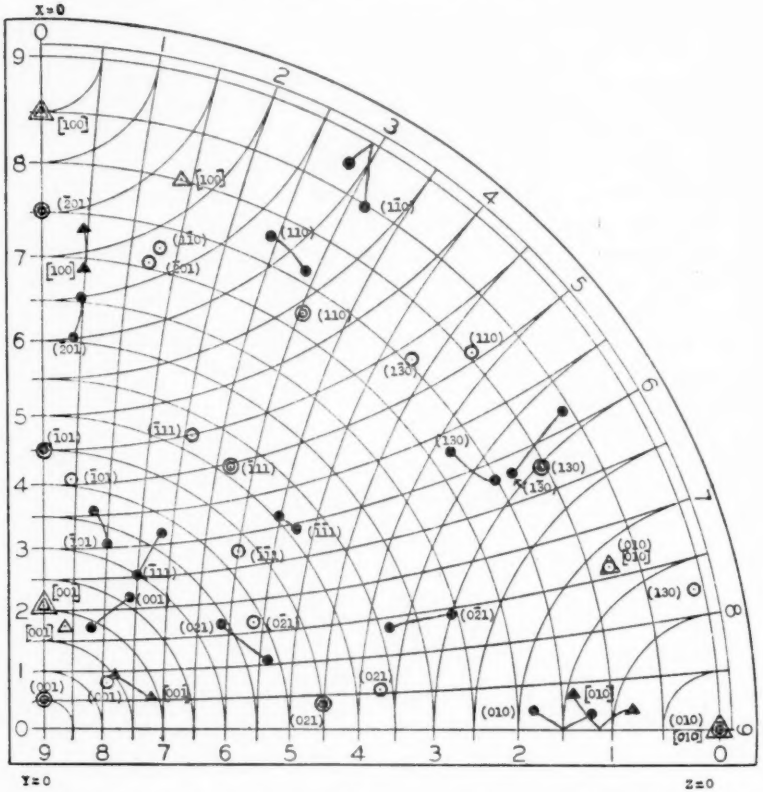

Fig. 4. Inclination of X, Y, and Z to axes and poles of faces in orthoclase, microcline, and albite. Triangles are axes; circles are poles of faces. Solid black points are albite (Ab_{100}-Ab_{90}) with label at pure albite; single circles and triangles are microcline; double circles and triangles are orthoclase.

A special case, of great importance in problems of diagenesis and cementation, is the determination of narrow rims (outgrowths) of secondary feldspar surrounding detrital feldspar grains, and of minute idiomorphic crystals of authigenic

feldspar. In such grains or outgrowths, whether seen in thin section or in individual grain mounts, it is commonly possible to locate approximately with a universal stage the positions of a number of crystal faces and the directions **X**, **Y**, and **Z**. These are plotted on a projection net (as in previous examples) and the three angles between the pole of each face and X, Y, and Z respectively are measured from the net and recorded. These angles are plotted from the appropriate corners of the stereographic diagram (after Nikitin, 1936, Pl. VII)reproduced as Figure 4, each set of three angles defining a point on the diagram. Even with the most favorable conditions and reliable measurements, the points thus obtained

TABLE III

Interfacial angles in feldspar to the nearest degree

		Orthoclase Microcline	Albite
(001) ∧ (010)	zone of a axis	90	86°24′
(001) ∧ ($\bar{1}$01)	zone of b axis	50	52
(001) ∧ ($\bar{2}$01)	zone of b axis	80	82
(010) ∧ ($\overset{+}{1}\bar{1}$0)	zone of c axis	59+	60+
(010) ∧ ($\overset{+}{1}\bar{3}$0)	zone of c axis	29+	30+
(001) ∧ ($\overset{+}{1}\bar{1}$0)	co-zonal	68	∧ (110) = 65; ∧ ($1\bar{1}$0) = 69
(001) ∧ ($\bar{1}$11)	co-zonal	55	∧ ($\bar{1}$11) = 56; ∧ ($\bar{1}\bar{1}$1) = 58
($\bar{1}$11) ∧ ($1\bar{1}$0)	co-zonal	57	55
($\bar{1}$01) ∧ ($\bar{1}$11)	co-zonal	27	26
(010) ∧ ($\overset{+}{1}\bar{1}\bar{1}$)	co-zonal	63	∧ ($\bar{1}$11) = 60½; ∧ ($\bar{1}\bar{1}$1) = 66
($\bar{1}$11) ∧ ($\bar{1}\bar{1}$1)	co-zonal	54	53
($\bar{2}$01) ∧ (110)	co-zonal	46	46
($\bar{2}$01) ∧ ($\bar{1}$11)	co-zonal	39	39
(110) ∧ ($\bar{1}$11)	co-zonal	85	85
(001) ∧ ($\overset{+}{1}\bar{3}$0)		78	∧ (130) = 74; ∧ ($1\bar{3}$0) = 80
($\bar{1}$01) ∧ ($\overset{+}{1}\bar{1}$0)		69	∧ (110) = 70; ∧ ($1\bar{1}$0) = 66
($\bar{1}$01) ∧ ($\overset{+}{1}\bar{3}$0)		78	∧ (130) = 80; ∧ ($1\bar{3}$0) = 74
($\bar{2}$01) ∧ ($\overset{+}{1}\bar{3}$0)		67	∧ (130) = 68; ∧ ($1\bar{3}$0) = 62
($\bar{1}$11) ∧ (130)		78	∧ (130) = 77; ∧ ($1\bar{3}$0) = 52
($\bar{1}\bar{1}$1) ∧ (130)		54	∧ (130) = 57; ∧ ($1\bar{3}$0) = 82
(110) ∧ ($\bar{1}\bar{1}$1)		57	57
($1\bar{1}$0) ∧ ($\bar{1}$11)		84	81

are not likely to coincide with labeled points representing the principal faces of feldspar, but by their proximity to labeled points they will serve to identify the faces measured and the nature of the feldspar. This identification can then be checked by means of interfacial angles and zone relations between faces. Particularly useful in this regard is the common face (and cleavage plane) {010}, since the angles between its pole and X, Y, and Z respectively vary significantly with the composition of the feldspars. Likewise, if the positions of any of the three crystallographic axes (a[100], b[010], c[001]) can be located on the projection net, the three angles between each of these axes and X, Y, and Z respectively can be plotted on Figure 4 and compared with the labeled axial points as a check on the identification of the feldspar in question. The axes are particularly useful in this connection because their mutual relations to X, Y, and Z vary considerably in the different feldspars.

Reference data.—Crystallographic and optical data used in determining low temperature feldspars by this method are

TABLE IV

Angles between X, Y, and Z and poles of common feldspar faces to nearest degree (After Nikitin, 1936, pp. 94-101)

	Orthoclase			Microcline			Albite (Ab_{100})			Albite (Ab_{90})		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
⊥ (010)	90	90	0	74	82	18	88	72	18	88½	78	12
⊥ (001)	85	5	90	82	13	79½	68	26	76	73	19	82
⊥ (110)	36	72	59½	49½	80½	42	28	78	66	33	76	61
⊥ ($1\bar{1}0$)	36	72	59½	22	72½	77	32	85	58½	28½	87½	61½
⊥ ($\bar{1}01$)	45	45	90	49	41	86	60	32	80	54½	36	82
⊥ (021)	86	45	45	85	53	37	73½	34	61	79½	38	54
⊥ ($0\bar{2}1$)	86	45	45	73½	38	56½	75½	64½	30	76	56	37
⊥ ($\bar{2}01$)	15	75	90	23	70½	78	30	60½	86	25	65	85
⊥ (130)	63	80	29½	78	89	12	57½	72½	38	62	75	32½
⊥ ($1\bar{3}0$)	63	80	29½	46½	75½	47	62	77	31½	58½	84	32
⊥ ($\bar{1}11$)	50½	51	63	45	52	69	65	30	75	58½	37½	72
⊥ ($\bar{1}\bar{1}1$)	50½	51	63	62½	43	60	61	51	52½	58½	50½	55
c [001]	69	21	90	73	17½	87	85	19	72	81	15	78
a [100]	5	85	90	17½	80	76	22	69	85	17½	73	85
b [010]	90	90	0	74	82	18	86½	76	14	88	82	8

tabulated in Tables III and IV. The interfacial angles cited are measured between the normals to (poles of) faces in question. Within the limits of error involved in universal-stage measurements, the angle between any two faces may in most cases be regarded as identical for feldspar of any variety or composition.

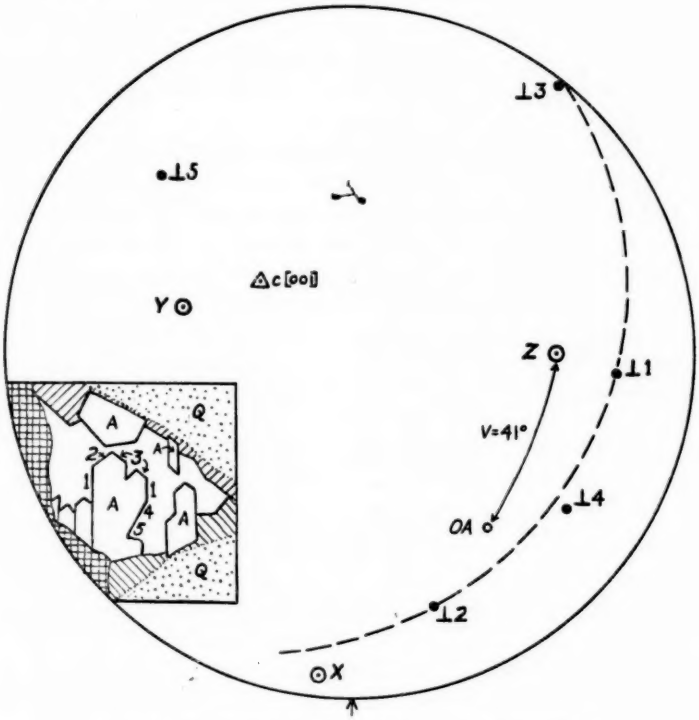

Fig. 5. Equal-area projection of albite (Example 4).

Example 4.—Authigenic albite from the Eocene McAdams sand of the Kettleman Hills area (U.C. #S3/10C) is illustrated by the equal area projection and inset sketch reproduced as Figure 5. In the sketch, the stippled areas are detrital quartz (Q) with secondary outgrowths shown by diagonal lines; cross-hatched areas are detrital feldspar, and euhedral crystals (A) are albite projecting into a cavity. The shapes of the albite crystals and the faces developed on them and

secondary quartz are not apparent unless the section is tilted; nor are they all apparent at any one position of tilt.

Measurements of X, Y, and Z, an optic axis, and the poles of all visible faces, made with a universal stage on the largest albite crystal, are as follows:

X	84 → 6	⊥ face #1	356 ← 24
Y	345 → 48 ↓ 29	⊥ face #2	288 ← 24
Z	0 ← 40	⊥ face #3	52 ← 2
		⊥ face #4	324 ← 24
		⊥ face #5	317 → 26

Plotted on the lower hemisphere of a equal-area projection net, these readings appear as the points shown in Figure 5. The three angles between X, Y, and Z and the pole of each face are read from the projection net and the faces tentatively identified by plotting these angles on the diagram reproduced as Figure 4, with the following results:

	∠X	∠Y	∠Z	Crystal form represented
⊥ face #1	88	72	17	(010) of Ab_{100}
⊥ face #2	28	88	61	($1\bar{1}0$) of Ab_{91}
⊥ face #3	34	76	60	(110) of Ab_{90}
⊥ face #4	60	75	34	($1\bar{3}0$) of Ab_{95} or ($13\bar{0}$) of Ab_{100}
⊥ face #5	61	31	77	($\bar{1}01$) or ($\bar{1}11$) of Ab_{100}

If the first four faces are correctly identified they must lie on a single great circle since they are all in the zone of the c axis (see Table III); as can be seen in Figure 5 this condition is satisfied. A further independent check on the identity of the faces can be made by determining the interfacial angles from the projection net and comparing these with the proper angles given in Table III. Face #5 in particular is not certainly identified by the angles between its pole and X, Y, and Z respectively, which indicate that it may be either (($\bar{1}01$) or ($\bar{1}11$); but the ambiguity is removed by referring to the interfacial angles. These prove that face #5 is the unit pyramid ($\bar{1}11$). Similarly angles to faces #2 and #3 prove that face #4 is ($1\bar{3}0$), not (130). The following tabulation shows the measured interfacial angles and, for comparison, the correct angles in italics.

	Λ⊥#2 (1$\bar{1}$0)		Λ⊥#3 (110)		Λ⊥#4 (1$\bar{3}$0)		Λ⊥#5 (I11)		(I01)
⊥ #1 (010)	62	*60*	59	*60*	29	*30*	62	*61*	*86*
⊥ #2 (1$\bar{1}$0)			60	*59*	33	*30*	58	*55*	*66*
⊥ #3 (110)					87	*89*	85	*85*	*70*
⊥ #4 (1$\bar{3}$0)							50	*57*	*80*

With the faces thus certainly identified, the c axis [001], can be located on the projection net since it is parallel to faces #1, #2, #3, and #4; that is, it is the pole of the great circle through the poles of these faces. Located as it is from four faces considered conjointly, the position of the c axis [001], is probably more reliable than the position of any single face. Its inclination to X, Y, and Z plotted on Figure 4 agrees closely with that of pure albite.

It is concluded that the idiomorphic feldspar crystal in question is nearly pure, untwinned albite having a Baveno habit. The smaller crystals present in the same cavity are similar but they have fewer faces developed. The accuracy obtained in these measurements is about all that can be expected with the universal stage, but great precision is not required for satisfactory identification, particularly if the angular relation between X, Y, and Z and one of the pinacoids or one of the crystallographic axis is known.

By the use of these methods and similar ones applied to quartz (see examples 2 and 3), the relationship between this albite and the secondary quartz outgrowths in contact with it can be determined. Quartz is molded around idiomorphic albite (particularly the upper left part of the sketch in Figure 5), but the albite crystals appear to have grown on top of thin quartz outgrowths. These latter bottom contacts of albite against secondary quartz are not rational faces of either mineral, and it is concluded that the two crystallized more or less simultaneously or that their periods of crystallization overlapped.

Example 5. — Authigenic feldspars are fairly numerous among the light minerals in the Santa Margarita sandstone, southern Santa Cruz County, California. Figure 6 is an equal-area projection of a crystal of authigenic orthoclase from this formation (U.C. #S1/29).

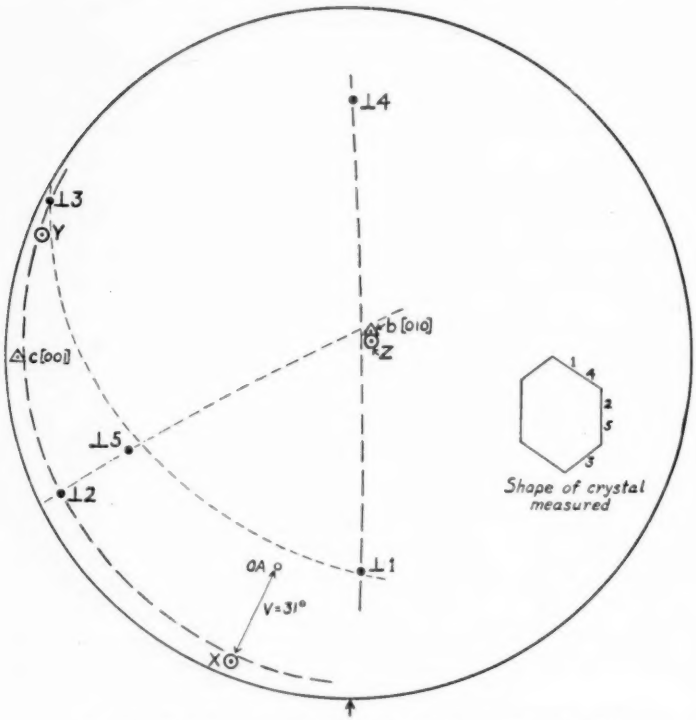

Fig. 6. Equal-area projection of orthoclase (Example 5).

The following measurements made with the universal stage were plotted on the projection net (Figure 6):

	X	69 → 4
	Y	339 → 4 ↓ 55
⊥	face #1	93 → 36
⊥	face #2	26 → 7
⊥	face #3	333 → 2
⊥	face #4	89 ← 28
⊥	face #5	24 → 30

The position of Z is plotted 90 degrees from X and Y. The angles between X, Y, and Z and the pole of each of the five faces is read from the projection net, and the probable form of each face is determined by plotting these angles on the diagram reproduced as Figure 4, with the following results:

	∧ X	∧ Y	∧ Z	Crystal form represented
⊥ face #1	39	74	56	{110} of orthoclase
⊥ face #2	43	47	89	{$\bar{1}$01} of orthoclase
⊥ face #3	85	6	88	{001} of orthoclase
⊥ face #4	37	71	60	{110} of orthoclase
⊥ face #5	49	49	66	{$\bar{1}$11} of orthoclase

An independent check on this identification of the faces may be obtained by measuring the interfacial angles on the projection net and comparing them with the correct interfacial angles for orthoclase (Table III). The agreement is good as shown by the following tabulations where the correct angles are italicized.

	∧⊥#2 ($\bar{1}$01)		∧⊥#3 (001)		∧⊥#4 (110)		∧⊥#5 ($\bar{1}$11)	
⊥ #1 (1$\bar{1}$0)	68	*69*	68	*68*	61	*61*	57	*57*
⊥ #2 ($\bar{1}$01)			53	*50*	70	*69*	28	*27*
⊥ #3 (001)					66	*68*	56	*55*
⊥ #4 (110)							85	*84*

Another independent check is obtained by using the b and c crystallographic axes. Since faces #1 and #4 are two faces of the unit prism, the c axis [001] is the normal to the great circle passing through the poles of these two faces; likewise the b axis [010] is the normal to the great circle passing through the poles of faces #2 and #3, ($\bar{1}$01) and (001) respectively. The angles between each of these axes and X Y, and Z are read from the projection net and plotted on Figure 4. Furthermore, the angles between each crystallographic axis and the poles of faces (other than those used to locate the axis) can be measured and compared with the correct angles for an additional check if necessary. In the present case, the agreement is good between all of these angles and the corresponding correct angles for orthoclase.

The zone relations between poles of faces, crystallographic axes, and indicatrix axes should also be checked in connection with this identification, particularly where combinations of three or more co-zonal faces are present. In the present example, faces #1 (1$\bar{1}$0), #3 (001), and #5 ($\bar{1}$11) should be co-zonal if they have been correctly identified; Figure 6 shows that they are. Likewise, faces #2 ($\bar{1}$01) and #5 ($\bar{1}$11) and the b axis [010] should be and are co-zonal within the limits of error of measurement. Also if faces #2 and #3 respectively

are ($\bar{1}01$) and (001) of orthoclase, the great circle containing their poles should include X, Y, and the c axis [001], a condition which is satisfied in Figure 6.

RAPID DISTINCTION BETWEEN QUARTZ AND CLEAR FELDSPAR

Statistical investigation of the relative amounts of the principal light constituents in sandstones involves rapid distinction between alkali feldspars (with refractive indices below that of Canada balsam), plagioclase (oligoclase or a more calcic variety), and quartz. Clear grains of plagioclase without obvious twinning are not uncommon and are difficult or impossible to distinguish quickly from quartz by ordinary means. The universal stage is an efficient device for this purpose. Its use has previously been recommended by Doeglas (1940), but the procedure outlined by him, namely, that required for general distinction of uniaxial from biaxial minerals, is unnecessarily complex. The problem involved is the particular case of distinguishing a *vositive* uniaxial mineral (quartz) from a biaxial mineral with large optic axial angle (feldspar), and can be solved simply and quickly as follows:

1) Set the north-south and east-west rotation axes of the stage near the zero positions. With the grain in question illuminated between crossed nicols, insert the gypsum plate and note whether the reaction is one of compensation or addition. Remove the plate and rotate on the innermost vertical axis of the stage so as to bring the grain into extinction with its slow direction (Z′) parallel to the north-south axis.

2) Tilt through any angle on the east-west axis of the stage. If the grain becomes illuminated (passes out of extinction), it is not quartz. If it stays in extinction for all positions of tilt on the east-west axis, it is probably quartz; but the same effect would result from a grain of feldspar oriented with X or Y parallel to the east-west axis of the stage—a most unlikely possibility.

3) To eliminate this latter possibility, tilt to any new angle on the north-south axis, and rotate on the innermost vertical axis until the grain is again in extinction with its slow direction (Z′) parallel to the north-south axis. If the grain again remains dark for all positions of tilt on east-west axis, it is uniaxial and positive (i.e., it is quartz).

If the grain is oriented with the optic axis nearly perpen-

dicular to the plane of the slide, the test may be more decisive if the gypsum plate is retained in position throughout. Extinction of the grain is then indicated not by darkness, but by the unmodified first order red color of the plate.

In practice the writers have found that a procedure involving steps #1 and #2 alone will yield reliable results in statistical work. The possible misidentification of quartz mentioned in step #2 is unlikely, but in any case the error arising from this cause is probably less than the sampling error in grain counts of 100 to 200 grains. Also the procedure described is used in practice only if a grain cannot be identified quickly by other means (refractive index, cleavage, or twinning). Carried out in this way the operation is very nearly as rapid as any other microscopic method involving counting, and is considerably more reliable.

OPTICAL DISTINCTION BETWEEN CALCITE AND DOLOMITE

Emmons (1943, p. 189) has described an optical method of distinguishing calcite from dolomite, based upon the difference in the refractive index of the extraordinary ray (epsilon) in these two minerals (1.50 in dolomite; 1.486 in calcite). With the north-south and east-west axes of the stage at zero, a section of carbonate bounded by Canada balsam is brought to extinction with the fast direction (e′) parallel to the north-south axis. The analyser is removed, and the section is tilted on the east-west axis until the refractive index of the carbonate exactly matches that of Canada balsam. Both the angular position around the inner vertical axis and the angle of tilt on east-west are read in order to locate e′ (for which R.I. = 1.540) on a projection net. The position of the optic axis (e) is now located in the usual way and plotted on the projection. The angle e Λ é (optic axis Λ é) is 29½ degrees in the case of dolomite, or 36 degrees for calcite. Smaller angles than 29½ degrees indicate ankeritic dolomite (e.g., 24½ degrees for dolomite in which there is 20% replacement of Mg by Fe).

The writers have found that a modification of this method may sometimes be applied in thin sections to grains of carbonate adjoining quartz—a condition commonly encountered where a sandstone is cemented by calcite or dolomite. The procedure is as follows:

1) Locate the respective optic axes in the carbonate grain (e_c) and in the adjoining quartz grain (e_q). On the projection net draw the great circles respectively normal to the two optic

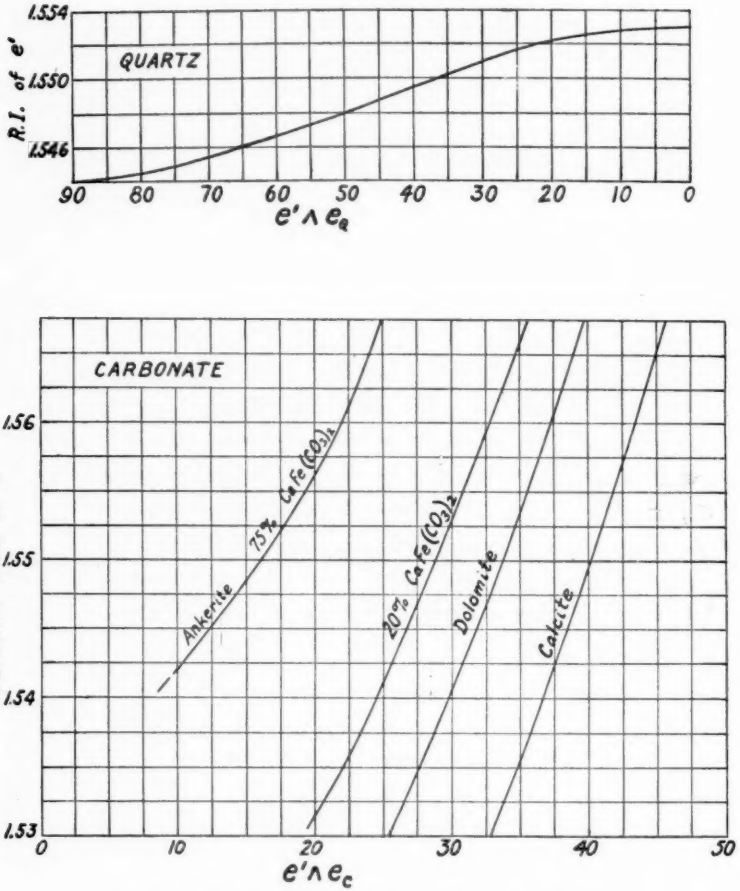

Fig. 7. Refractive index of é in quartz and carbonate.

axes. These great circles intersect in a point representing a common line lying in the basal planes of both crystals, and which is therefore a possible ordinary ray direction for both quartz and carbonate.

2) With the east-west axis at zero, rotate the section on the innermost vertical axis and tilt on the north-south axis so as to bring the common ordinary ray direction parallel to the east-west axis. (The appropriate angles of rotation and tilt are first read from the projection). If these two operations have been performed accurately, both grains will remain in extinction for any angle of tilt on the east-west axis.

3) With the analyser removed, tilt on the east-west axis until the refractive indices of the quartz and carbonate exactly match. Light in both crystals is now vibrating north-south in a common direction (e′), which is plotted on the projection net. The angle between e′ and the optic axis of quartz (e_q) is now read from the projection net and the refractive index of e′ determined from the upper curve of Figure 7. This index of refraction plotted against the angle between e′ and the optic axis of carbonate (e_c) on the lower set of curves in Figure 7 should identify the carbonate.

Quartz-carbonate pairs in which one of the two grains is oriented with its optic axis nearly normal to the plane of the section are most favorable for measurement, since only a small angle of tilt is then necessary to bring the common ordinary ray direction parallel to the east-west axis (step 2). The degree of reliability of this method, whether as originally described by Emmons or in the modified form just presented, depends mainly on the accuracy with which the refractive index of a mineral may be matched with that of the adjacent medium. In the writers' experience the range of determined values in the angle of $e_c \wedge e'$ in grains of a single carbonate mineral is in some cases too great for reliable identification of the mineral as calcite or dolomite. In other cases where clear-cut boundary surfaces between the media were readily observed and a good research microscope was used, the results were found to be consistent and distinction between calcite and dolomite was made with some confidence. Distinction of ankeritic dolomite from calcite is more reliable on account of the higher refractive index of the former mineral as compared with pure dolomite.

ACKNOWLEDGMENTS

The methods discussed in this paper have been applied and developed during investigations of California sandstones car-

ried out at the University of California with the encouragement and support of the Standard Oil Company of California. To this company and its Chief Geologist, W. S. W. Kew, the writers' thanks are here gratefully expressed. We are also indebted to Mr. Martin G. McAndrews for permisison to publish data on specimens of heulandite collected and examined by him in the course of research as a graduate student at the University of California.

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A NOTE ON TWO ASPECTS OF THE GEOCHEMISTRY OF CARBON

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ABSTRACT. Examination of the best data for the C^{12}/C^{13} ratio indicates that the carbon of the sediments as a whole, when any reasonable ratio of shales to limestones is assumed, contains less C^{13} than does the carbon of meteorites. The rather meagre comparable data give means for meteoritic and for igneous carbon that differ significantly. If Rankama is correct in assuming that the meteoritic ratio characterizes the earth as a whole, there must have been a slight non-biological impoverishment of C^{13} in the superficial part of the lithosphere. It is, however, equally likely that the meteorites do not provide a reliable terrestrial standard. Rankama's figures for the ratio in the carbon of *Corycium* are significantly different from those for igneous carbons, but not from those for meteoritic carbons. His conclusion that *Corycium* is an Archaean fossil is only valid if some difference between meteoritic carbon and that of the accessible lithosphere be assumed.

The available data for methane production by domestic animals and for the populations of such animals indicates at least 45 million metric tons of methane are liberated into the atmosphere per year. There are many other terrestrial sources of methane and a figure of 90 million metric tons may well be too low. This represents about 0.06% of the carbon circulating in the photosynthetic cycle. Mechanisms of oxidation of CH_4 must operate, either photochemically in the stratosphere or biologically in the soil.

THE two aspects of the geochemistry of carbon discussed below, though not closely related, are conveniently presented together.

I. THE TERRESTRIAL $C^{12}/^{13}$ RATIO

In two papers of great importance Rankama (1948a, b) has examined all the available data, including a number of new determinations, on the ratio of C^{12} to C^{13} in meteoritic and terrestrial materials. The marked difference between the carbon of sedimentary carbonates and the reduced carbon of bituminous sediments and recent and fossil plants, first noticed by Nier and Gulbransen (1939) is firmly established, and is used by Rankama as an argument that the problematic structures known as *Corycium enigmaticum* Sederholm from the Bothian phyllites of Finland are actually genuine Archaean fossil plants. This argument, though subject to slight modification, is almost certainly correct. There is, however, one aspect of the treatment of the data that demands further consideration.

Using only the data obtained by Murphey (Murphey and

Nier, 1941, Rankama 1947a) and by Rankama himself, which data are known to be instrumentally uniform and so comparable, the following ranges and mean values are available,

Meteorites (7 determinations)	89.8-92.0	mean *91.26*
Igneous graphite and calcite (4 determinations)	89.4-90.2	mean *89.82*
$CaCO_3$ sediments (13 determinations)	88.4-89.5	mean *89.15*
Carbonaceous sediments (18 determinations) including *Corycium*)	90.3-92.9	mean *91.88*
Known recent and fossil plants (29 determinations	91.3-93.1	mean *92.02*
Corycium carbon (3 determinations)	90.8-92.0	mean *91.4*

Statistical examination, using the *t*-test (Fisher 1934) for the significance of two means indicates that,

1.) The meteoritic and igneous carbons show a highly signnificant difference ($P<0.01$)

2.) The calcareous sediments and the igneous carbons show a highly significant difference ($P<0.01$)

3.) The bituminous sediments and the igneous carbons show a highly significant difference ($P<0.01$)

4.) The bituminous sediments and the meteoritic carbons show a difference of very moderate significance ($P = 0.03$)

5.) *Corycium* carbon by itself is not significantly different from meteoritic carbon ($P = 0.8$) but the difference between *Corycium* carbon and igneous carbon does have a high degree of significance ($P<0.01$)

The bituminous and carbonaceous sediments and the plant carbons are obviously concordant and a weighted mean of 91.97 is therefore the best value for the reduced carbon of the biosphere.

Rankama believes that the best estimate of the ratio for the earth as a whole is obtained from meteorites. As Wickman (1941) and independently Kamen (1946) pointed out, the values of the ratios for oxidized and reduced carbon in the sediments must be related to the total means of such oxidized and reduced carbon, the quantity of carbon in the atmosphere and hydrosphere being negligible. If the mean of the available data for the meteorites is taken as a standard, the divergences from this standard are

oxidized C ($CaCO_3$)	reduced C (plant and bitumen)
−2.11	+0.71

These divergences imply about three times as much reduced as oxidized carbon in the sediments, a conclusion which is quite inconsistent with the rest of the available geochemical evidence.

The argument introduced by Wickman may, however, be reversed. Taking as an extreme estimate (Kuenen 1941 for continental sediments), the limestones as comprising 15% of the sediments, containing 11.35% carbonate carbon, and the shales 65% of the sediments, containing 0.81% carbon (cf. Clarke 1924, Kuenen 1941, Conway 1942, Hutchinson 1944), the ratio of oxidized carbon to reduced carbon will be 1.703 : 0.526 or 3.24 : 1. To obtain such a ratio the original material, separated on the one hand into carbonate $C^{12}/C^{13} = 89.15$), on the other into reduced organic carbon ($C^{12}/C^{13} = 91.97$) would have had an isotopic ratio of 89.82, or precisely that obtained from a consideration of the rather meagre material derived from the accessible igneous rocks. Alternatively taking the more usual estimate of 5% limestones and 80% shales (Clarke 1924) which perhaps underestimates the limestones, the same reasoning leads to a figure for the original ratio of 90.66. The true value probably lies between these two extremes. It is evident that if Rankama is correct in his belief that the meteoritic ratio is also the ratio for the earth as a whole, some prebiological impoverishment of C^{13} has occurred in the superficial layers of the lithosphere, in the production of the magmas which, on solidification, produced the igneous carbons, and in the production of the volcanic gases from which the sedimentary carbons are ultimately derived. The fact that neither the igneous carbons nor the volcanic gases need be primary is irrelevant. The mass relations show unequivocally that the meteoritic mean cannot apply to the original material of the accessible lithosphere and of the biosphere. If the meteoritic mean applies to the whole earth, then clearly a non-biological process produced slight impoverishment in C^{13} in the superficial layers at an earlier stage than the separations involved in calcium carbonate precipitation and photosynthetic fixation.

As an alternative to the hypothesis that a non-biological separation occurred in the earth's crust, it may be urged that the meteoritic ratio is not inherently likely to be applicable to the earth. At any given temperature the mean molecular velocity of any gaseous compound of C^{13} will be slightly less

than that of the analogous compound of C^{12}. Since it is reasonably certain from the high cosmic and low terrestrial abundance of the element that the earth lost a considerable amount of carbon early in the history of its cooling, the mean terrestrial value of the ratio C^{12}/C^{13} presumably is a function, among other things, of the mass of the earth. An identical ratio therefore would be expected only if the meteorites were derived by fragmentation of a planet of the same mass as the earth. While the elegant researches of Brown and Patterson (1948) have greatly increased the probability that the meteorites are in fact the products of the fragmentation of a terrestrial planet, it would be premature to assume that in such a planet the C^{12}/C^{13} ratio could not have differed from that of terrestrial carbon. The differences observed between igneous and meteoritic carbon may therefore depend on original differences established during the cooling of the earth and of the hypothetical planet. Further determinations of the isotopic ratio in carbon from meteorites and from igneous rocks are obviously urgently needed. In particular a study of the distribution of ratios in a long series of meteorites might produce information of considerable importance. Meanwhile it is important to note that the statistical treatment given above indicates that Rankama's argument about *Corycium* is dependent on the primary carbon source of the biosphere differing from meteoritic carbon in the way in which it does in fact appear to differ.

II. THE METHANE CYCLE IN THE BIOSPHERE

Benedict and his coworkers have shown that fermentation in the alimentary tract of large herbivores gives rise to so much methane that a significant proportion of the carbon in the

	Methane per indiv. per day	Methane per indiv. per year	Population	Total Methane per year
Horse	106 gr.	37.7 kgm.	99.8×10^6	3862.10^3 metric tons
Cattle	200 "	73.0 "	510.9×10^6	37296.10^3 " "
Goat	14.7 "	5.4 "	116.8×10^6	631.10^3 " "
Sheep	15.1 "	5.5 "	532.2×10^6	2927.10^3 " "
Elephant	470.0 "	171.5 "	$0.5^* \times 10^6$	86.10^3 " "
				44802.10^3 " "

* Crude guess from ivory production of world.

organic matter ingested by these animals is returned to the atmosphere as CH_4 rather than CO_2. Mrs. Jane K. Setlow has prepared the preceding table, using the metabolic data of Ritzman and Benedict (1938) and the figures for approximate world populations collected by Rew (1929).

The total methane production of the biosphere must be very much greater than the estimated 45 million metric tons expired by these animals. Although it is possible that the estimates given above are based on animals better fed than the average, not only must extensive production by wild herbivores other than the elephant be considered, but also the vast methane production of lakes and swamps, for which a quantitative estimate is at present not possible. It would probably be quite safe to double the estimate derived from the table, giving a total annual production of 90.10^6 metric tons. Since the total photosynthetic fixation of carbon is about 150.10^9 tons per year (Riley 1944) it would appear that about 0.06% of the element circulating in the biosphere enters a subsidiary part of the carbon cycle as methane. It is also evident that this subsidiary path is truly cyclical, otherwise very large quantities of methane would have collected in the atmosphere.[1] At least two geochemical mechanisms of oxidation of this methane appear to exist, namely photochemical oxidation in the stratosphere and bacterial oxidation in soils. It is impossible to estimate which of these processes is likely to be quantitatively the more important.

It is well known that if an estimate be made of the total atmospheric oxygen together with the oxygen lost to the sediments in the oxidation of ferrous iron, the resulting quantity is very much less than the oxygen equivalent of the reduced carbon of the sediments. It seems, however, that such reduced carbon must have been mainly derived from CO_2 by photosynthesis. The excess carbon has been explained as derived from methane or carbon monoxide of volcanic origin, or as an apparent excess due to loss of gaseous oxygen through combustion of volcanic hydrogen. Since it seems likely that some hydrogen, carbon monoxide and methane

[1] A small stationary concentration would be expected and after this paper had gone to press my friend, Dr. Rupert Wildt, called my attention to the recent work of Marcel V. Migeotte (Astrophys. Jour. 107: 400-403, 1948) in which a qualitative demonstration of the presence of such a small stationary concentration in the earth's atmosphere is actually given.

would escape from volcanic vents prior to combustion, the demonstration of a large scale production and oxidation of methane in the biosphere is of some geochemical interest, particularly since the mechanisms responsible for oxidation of methane are likely also to operate in the oxidation of carbon monoxide and hydrogen. Conway (1942) has indicated the probable existence of similar mechanisms involved in the oxidation of hydrogen sulphide.

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A PRELIMINARY STUDY OF THE FLORA OF THE BRANDON LIGNITE

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ONE hundred years ago an unusually interesting and significant lignite deposit was accidentally discovered in the township of Brandon, Vermont. The deposit was encountered at considerable depth in the course of sinking a shaft for the extraction of underlying iron ore. The unexpected occurrence of brown coal in central Vermont almost immediately focused local scientific interest on the "Brandon lignite" and its geological and paleobotanical significance.

In 1851 Professor Shedd of the University of Vermont collected and sent specimens of the curious and abundant lignitized fruits from the deposit to Prof. Edward Hitchcock, then President of Amherst College and State Geologist of the Commonwealth of Massachusetts. Hitchcock visited the Brandon site the following spring and published a brief account of the Brandon lignite and associated strata which, he concluded, was "the type of a Tertiary formation hitherto unrecognized as such, extending from Canada to Alabama." (Hitchcock, 1853.) A collection of the seeds and fruits was sent by Hitchcock to Leo Lesquereux, the eminent Swiss-American paleobotanist. Lesquereux described and named a series of "species" of which several were botanically "identified" and the remainder assigned to the paleobotanical form-genus *Carpolithes* (Lesquereux, 1861).

The contributions of Hitchcock and Lesquereux, despite certain flaws in generalizations and conclusions, present a remarkably clear interpretation of the Brandon lignite deposit, particularly in view of the paucity of collections and data at their disposal. In retrospect their achievement is more apparent when it is recognized that little has been added to a satisfactory understanding of the deposit since the middle of the last century.

The Brandon deposit of lignite was accidentally "rediscovered" in 1901-02 in the course of clay mining operations at the same locality in which it was found in 1848. Rediscovery of the lignite coincided with the coal strike of 1902 and this

combination of events led for a short time to the local utilization of the brown coal as a fuel. G. H. Perkins, State Geologist of Vermont, became keenly interested in the deposit, particularly its botanical aspects, and secured the coöperative interest of several paleobotanists and geologists in a study of the deposit and its geological relations. As a result of these investigations a series of papers were published on the flora of the Brandon lignites (Knowlton, 1902; Ami, 1906; Jeffrey and Chrysler, 1906; Perkins, 1904, 1906). Perkins' contributions, though extensive, were confined to descriptive analyses of the fossil fruits of which he enumerated 148 "species." Despite the completeness of the material he collected and examined, Perkins' studies provide little critical botanical information in the determination of the flora. As a result of his efforts, however, a very large series of the characteristic fossil forms from the lignite were adequately illustrated and carefully described as to gross features.

The geological relations of the deposit and associated strata were investigated and briefly described by T. Nelson Dale (1904) and J. B. Woodworth (1904). Their conclusions largely supplemented the earlier interpretation of the deposit made by Hitchcock.

The major problems centering on the lignite deposit at Brandon have remained unsolved despite the rather numerous but disjunct contributions during the last century. These problems are both paleobotanical and geological and comprise three major questions: (1) the botanical composition of the deposit and the significance of the flora in terms of phylogeny, vegetational history and paleoclimatology; (2) more exact determination of the age of the deposit and its possible correlation with other known Tertiary floras; (3) interpretation of the anomalous stratigraphic position of a presumably early or mid-Tertiary deposit occurring virtually at present stream level on a supposedly late Tertiary erosion surface.

Because of its unusual botanical and geological significance, the writers have undertaken an extensive investigation of the Brandon lignite. The summer of 1947 was spent in locating the lignite mass and in removing material for subsequent study. The lignite is concealed by both glacial drift and tailings from abandoned clay mining operations. Extensive core drilling was necessary to determine the position and depth of the

deposit. Fortunately, exposure of a large mass of lignite was made within a few feet of the surface and small scale stripping and blasting operations revealed a considerable area of both lignite and associated organic sediments. Six tons of lignite were removed in the latter part of the summer and it is intended that additional material be obtained during the coming field season.

The Brandon deposit is located approximately 250 feet east of the Forestdale-Rutland road about one-half mile south of the village of Forestdale, Brandon. The lignite and associated clays, ochres, iron and manganese ores underlie a limited area on a tract of land owned by Mrs. Gertrude S. Horn of Forestdale. The deposit is close to the concealed and uncertain zone of contact of the Lower Cambrian Cheshire Quartzite and the Lower Cambrian Dunham Dolomite.

In contrast to many American lignites the Brandon deposit contains abundant remains of well preserved fruits and seeds as well as twigs, branches and larger wood fragments. The plant tissues are unmineralized and amenable to sectioning and anatomical study by the ordinary histological methods. In addition to fruits, seeds and woody fragments the deposit contains an abundance of diverse pollen grains, representing an estimated 100 species. Leaf remains are fairly common but are represented by small fragments only. With the exception of the pollen grains of *Pinus* all plant remains which have been thus far identified are those of dicotyledons and monocotyledons; the latter are represented by pollen grains only.

The presence of a wide range of various plant parts within a single deposit provides an opportunity to employ a highly desirable but little exploited paleobotanical "technique." This "technique" consists of utilizing concurrently all available collateral evidence in the botanical determination of the plants represented in the fossil flora. By this procedure determinations may be checked or verified with evidence derived from a wide range of sources, viz., wood structure, nodal anatomy, leaf epidermis, seeds, fruits and pollen. Correlation of the various lines of evidence makes it possible to verify or to preclude doubtful determinations based solely upon one category of evidence. The application of the method to the study of Tertiary floras necessitates extensive familiarity with the anatomy and morphology of living Angiosperms. In the

opinion of the writers, however, it is the only feasible approach to the complex problems of identifying fossil Angiosperms.

Preliminary analysis of the Brandon flora shows the presence of characteristically warm temperate genera represented by *Nyssa*, *Cyrilla*, *Persea*, *Bumelia*, *Quercus* (live oak group), *Vitis* (section Muscadinia), *Symplocos*, and *Ilex*. With the exception of *Ilex*, all of the genera are represented by seeds, fruits, or wood. Tentative identifications of additional genera have been made on the basis of pollen grains. In view of the richness and complexity of the flora, however, collateral evidence is being sought to confirm many such identifications based upon pollen alone. Examination has been made of the pollen of over 400 living species of temperate, warm temperate, and sub-tropical species comprising a wide range of families of the dicotyledons. As a result of this survey the intrinsic difficulty of accurate identification of fossil pollen has been strongly impressed upon the writers. The occurrence of remarkably similar pollen types in remotely related groups of the Angiosperms clearly indicates the need for extreme care in the determination of genera. In contrast to the relatively depauperate woody floras of temperate Quaternary peats the pollen flora of Tertiary deposits present a far more complex picture. It is probable that the pre-glacial floras of northeastern America were richer in both species and genera than the forest associations of the same areas today. In the Brandon flora there is considerable evidence of several genera which are now confined to southeastern Asia. From the available evidence, however, the Brandon deposit represents an assemblage of genera now living in close association in the southeastern United States. In this connection it is significant that of 400 specimens of wood from the Brandon deposit a very large per cent represent the genus *Cyrilla*. *Cyrilla racemiflora* in the modern flora is a small tree or shrub abundant in the lowland swamp forests of the Gulf States.

One of the most interesting and significant groups represented in the Brandon lignite is the family Nyssaceae. As the result of histological studies a particularly striking series of fruits designated by Perkins as *Monocarpellites*, *Bicarpellites*, *Tricarpellites*, and *Glossocarpellites* have proved to be endocarps of Nyssaceous fruits. Several of the two and three carpellate forms are comparable to the London Clay fruits *Pro-*

tonyssa and *Paleonyssa* described by Reid and Chandler (1933). *Nyssa* endocarps of the "*Glossocarpellites*" series range up to 5 centimetres in length and average far larger than any fossil or living members of the *Nyssaceae* known to the authors. In the living flora the only approach to the larger Brandon forms is *Nyssa megacarpa*, a poorly known species from the mountains of Burma (Parker, 1929).

Nyssoid endocarps are remarkably abundant in the Brandon lignite. The genus *Nyssa* was apparently represented in the swamp forests of Brandon time by a larger number of species than exist today in eastern America. In addition, the numerous massive two and three carpellate endocarps unquestionably represent extinct genera closely allied to *Nyssa*. The nyssoid forms as a group are of exceptional interest in demonstrating a coherent phylogenetic series. The series clearly indicates that evolution in the *Nyssa* complex has involved both reduction in the number of carpels and reduction in thickness of the endocarp wall. The significant features of this phylogenetic series have been elucidated by histological study and anatomical comparison of the fruits of living *Nyssa* with the fossil forms.

The stratigraphic relations of the Brandon lignite deposit are complex and confused. In the absence of associated marine or fresh water invertebrates there is no direct method available for dating the deposit. The composition of the flora, its marked difference from the modern flora of similar latitudes, and particularly the presence of extinct genera all suggest considerable antiquity for the Brandon deposit. The obviously warm temperate aspect of the flora is strong evidence in favor of this view. From the accumulated and harmonious evidence regarding the Tertiary floras of western Europe, western and southeastern North America, it is apparent that the earlier Tertiary floras were characterized by the northward extension of many genera now limited to the lower middle latitudes of the north temperate regions. In view of these considerations it would seem logical to regard the Brandon flora as early or mid-Tertiary in age. Such an assumption, however, is based primarily upon paleoecological rather than direct floristic evidence or correlation.

The possible early or middle Tertiary age of the Brandon lignite is somewhat inconsistent with its present physiographic

relationships. Because the lignite lies in the valley floor, almost at present stream level, it is difficult, without invoking special circumstances, to regard the deposit as older than Pliocene or at most late Miocene, the presumed age of the pre-glacial erosion surface on which the lignite was deposited. This interpretation is based on the assumption that western New England was subjected to a series of uplifts in early and middle Tertiary time with the resulting formation of erosion surfaces discernible in the present topography. If this view of the physiographic history be correct it is obviously difficult to assign the lignite deposit to the early Tertiary, the age which is more consistent with paleobotanical evidence. On the other hand there is no critical botanical evidence to establish the Eocene age of the Brandon flora as proposed by Berry and others (Berry, 1919). It is apparent, therefore, that the problem of the age of the Brandon lignite cannot be resolved until more is known of its geological relations and its possible paleobotanical correlation. It should be emphasized, however, that the deposit and its associated clays, ochres, and ores cannot be referred to the early Tertiary without necessitating a thorough reinterpretation of the Cenozoic erosional history of western New England.

It is proposed to summarize the results of present studies of the Brandon lignite in a series of forthcoming papers dealing with discrete phases of the problem. Tertiary floras of the southern and western United States have been intensively studied within the last few decades (Chaney, 1940). Similarly numerous critical studies have recently been made of the Cenozoic deposits of western and central Europe (Kirchheimer, 1939, 1942; Thiergart, 1940; Hirmer, 1942). In marked contrast, the composition of the Tertiary flora of the northeastern United States is virtually unknown, largely because of its meagre preservation in the fossil record. The Brandon lignite deposit is one of an exceedingly few clues to the origin and development of the pre-glacial vegetation of northeastern North America.

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THE GALLIUM CONTENT OF IGNEOUS ROCKS

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ABSTRACT. Analysis of composite samples indicates a Ga/Al weight ratio varying from 1.5×10^{-4}, or somewhat less, in basic rocks to 3×10^{-4} in granites high in silica. There is some indication that gallium may replace ferric iron in minerals. The abundance of gallium in the upper lithosphere is estimated to be 15 parts per million.

THE most comprehensive investigation of the geochemistry of gallium was made by Goldschmidt and Peters (1), who particularly pointed out the close association of gallium and aluminum in silicates and showed that the ratio of gallium to aluminum increased in late differentiates. In a later paper, Goldschmidt and coworkers (2) reported figures for the gallium content of German granites, gabbros, shales, and greisen. Since that time, data on the abundance of gallium in rocks have been given by van Tongeren (3), Rankama (4), Wager and Mitchell (5), and Sahama (6, 7), as well as others. Nockolds and Mitchell, in a noteworthy contribution (8), have reported the gallium content of the component minerals of Caledonian plutonic rocks from western Scotland, as well as of the rocks themselves. Erämetsä (9) studied the distribution of gallium in Finnish minerals, mostly silicates. Other workers, especially Russian, have also investigated the occurrence of gallium in minerals.

In the present work an attempt has been made to fix somewhat more exactly than previously, the gallium-aluminum ratio in igneous rocks and at the same time to obtain some data on the abundance of the element in common rocks. For this purpose, samples previously analyzed for the major constituents were taken, and determinations were run on composite samples (Table I) and also on some individual samples (Table II).

METHOD OF ANALYSIS

Previous workers have determined trace concentrations of gallium by optical spectrography. The present results were obtained by an independent method which involves extraction of gallium chloride by ethyl ether from a hydrochloric acid solution of the decomposed sample, followed by fluorimetric determination of gallium as the 8-hydroxyquinolate in chloro-

TABLE I

Gallium in Composites of Igneous Rocks

Silica Range % SiO_2	Average Silica % SiO_2	Average Alumina % Al_2O_3	Rock Type and Number of Samples	Region	Gallium Content P.p.m. Ga		Ga/Al x 10^4
80.6–76.3	77.7	11.6	Granite (12)	U. S.	18.5, 16.5	17.5	2.9
81.5–75.1	77.0	11.7	Granite (8)	U. S. and Canada	18.5		3.0
77.4–71.5	74.1	13.75	Granite, etc. (9)[a]	California	15		2.1
76.8–68.2	73.1	13.7	Granite (5)	Texas (Llano region)	17.5, 17.0	17	2.3
74.3–70.6	72.6	14.2	Granite (7)	Canada	16.5		2.2
73.9–70.0	72.0	14.5	Granite (9)	Africa	14.5, 16	15	2.1
69.6–65.5	68.4	15.3	Granite, etc. (14)[b]	[c]	15.5		1.9
65.7–52.7	62.0	15.9	Diorite (7)	Oregon and California	15		1.8
57.7–44.4	50.0	15.7	Basic (24)[d]	[e]	13.5, 11, 11.5	12	1.4
51.3–45.7	47.6	18.8	Gabbro-diorite (4)	California	17		1.7
50.4–46.0	47.4	16.8	Basalt	Michigan[f]	17.5		2.0
54.7–33.4	42.8	1.7	Sub-basic (6)[g]	[h]	1.5		1.5±
53.2–48.3	50.7	28.7	Anorthosite (3)	New York, Minnesota and Montana	20[i]		1.3
64.1–56.0	60.3	17.5	Syenite (6)	New York and Minnesota (1)	21, 22	22	2.4
57.9–49.6	53.1	18.3	Phonolite (4)	Africa	22		2.3

[a] 4 granites, 2 quartz monzonites, 1 monzonite, 2 granodorites.

[b] 6 granites, 1 granite porphyry, 1 feldsite porphyry, 1 porphyry, 1 quartz monzonite, 1 granodiorite, 1 diorite, 2 dacites.

[c] Canada 2, New York 1, Texas 2, Montana 2, Wyoming 1, California 2, 4 from unspecified U. S. or Canadian localities.

[d] 9 gabbros, 1 norite, 4 diabases, 8 basalts, 1 peridotite, 1 pyroxenite.

[e] Eastern and Western U. S. 13, Newfoundland 1, Africa 1, Antarctica 3, India 1, unspecified localities (probably U. S.) 5.

[f] Weighted composite of Greenstone flow.

[g] 1 peridotite, 1 dunite, 1 harzburgite, 1 bronzitite, 1 pyroxenite.

[h] Newfoundland 3, U. S. 2.

[i] Average from 3 individual anorthosite values in Table II.

form solution (10). Ordinarily a 0.2 or 0.25-g. sample is taken and a 4/10 aliquot of the solution is used for the determination. As little as 1 part per million of gallium can be detected in the sample. If the amount of sample is limited, the analysis can be made on 0.05 g. of material. The fluorimetric determination is made visually by comparison against a standard. The precision of the comparison corresponds to an error of about 10 per cent. The recovery of known amounts of gallium carried through the procedure averaged better than 90 per cent for the range 5 to 50 p.p.m. of gallium. To compensate the tendency toward slightly low results, the experimental values have been multiplied by the factor 1.1, and these corrected values are the ones given in the tables.

TABLE II

Gallium in Various Igneous Rocks

	Al_2O_3 %	Fe_2O_3 %	Ga P.p.m.	Ga/Al x 10^4
Rhyolite, Cook County, Minn. (12, Table 3, No. 1)	13[a]	—	16	2.5±
Pantellerite	8.9	7.3	41	8.7
Diorite, Little Falls, Minn. (12, Table 3, No. 17)	17.5	3.7	16.5	1.8
Diabase, Grand Marais, Minn. (12, Table 3, No. 9)	14.5	7.4	19	2.4
Diabase, Lake County, Minn. (12, Table 3, No. 14)	21.0	3.3	15.5	1.4
Harzburgite	5.0	4.0	4	1.5
Peridotite	3.0	0.7	2	1+
Dunite	0.4	0.8	<1	—
Augite syenite	15.1	6.0	25	3.1
Shonkinite	8.5	7.7	23	5
Anorthosite, Montana	28.9	0.6	19	1.3
Anorthosite, Split Rock, Minn.	30.7	0.2	20	1.2
Anorthosite, New York State	26.6	0.4	21	1.5

[a] Approximate value; figure from an old analysis of a different specimen from the same locality.

DISCUSSION OF RESULTS

The gallium-aluminum ratio. On the assumption that the distribution of gallium is controlled chiefly by aluminum, weight ratios of gallium to aluminum have been calculated for the samples listed in Tables I and II. The variations of Al_2O_3 and of the ratio Ga/Al with silica content is shown in Figure 1. It is seen that Ga/Al generally increases as differentiation proceeds toward silicic or alkali-rich products. This ratio has

a value of 1.5×10^{-4} or slightly less for the more basic rocks and for anorthosites, and increases to 3×10^{-4} in the high-silica granites. Between these two average extremes fall the

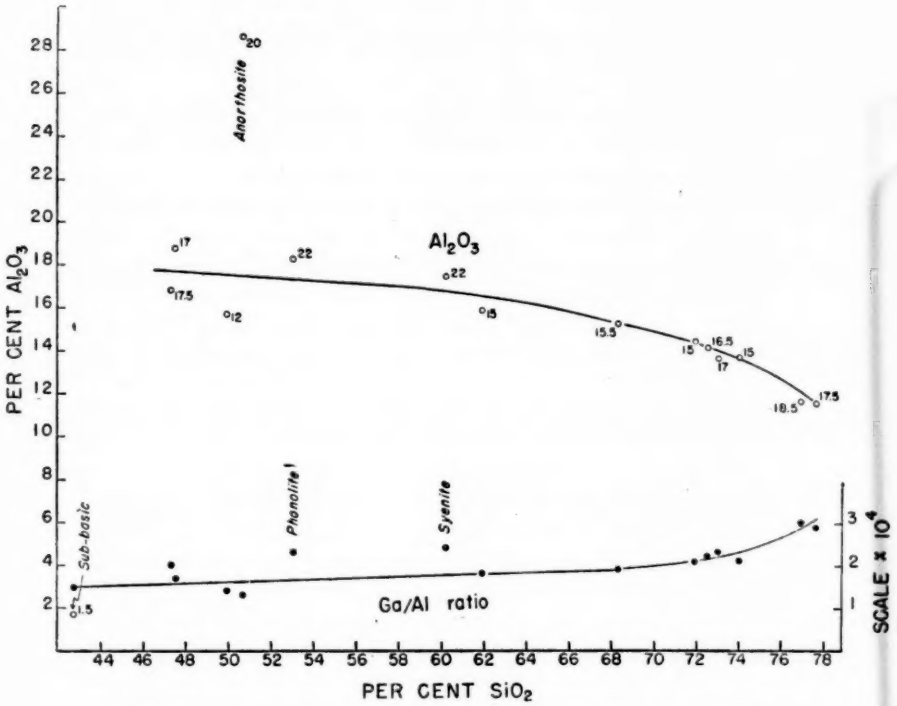

Fig. 1. Variations of Al_2O_3 and the ratio Ga/Al with SiO_2 for groups of rocks. The numbers give the content of gallium, p.p.m., in the composite samples.

values for intermediate rocks and the less silicic granites. The ratio is uncertain for rocks very low in aluminum because the error in the determination of the very small amount of gallium present is then large, but it seems to be near 1 or 1.5×10^{-4}.

For the granites and anorthosites, in which most of the gallium is present in the feldspars, the ratios given should be close to the substitution ratios for gallium in the lattice. When

relatively much ferric iron is present in a mineral there would seem to be a possibility that gallium can substitute to some extent for iron as well as for aluminum. Goldschmidt's empirical ionic radii for aluminum, gallium, and ferric iron are respectively 0.57, 0.62, and 0.67A. Apparently the ionic sizes of trivalent iron and gallium are sufficiently similar to permit mixed crystal formation. Because of the narrow range over which Ga/Al normally varies, the relatively large possible error in the determination of gallium, the general preponderance of aluminum over ferric iron in igneous rocks and the possibility of oxidation of ferrous iron to ferric, it is difficult to demonstrate convincingly the replacement of ferric iron by gallium. However, in some rocks of the basic type, in which no particular enrichment of gallium is apparent, the gallium-aluminum ratio is significantly greater than in silicic rocks. Thus, a diabase from Grand Marais, Minnesota (Table II), shows a Ga/Al ratio of 2.4×10^{-4} (from the mean of two concordant gallium determinations), which is equal to, or greater than, that of ordinary granites. This rock has a high content of ferric iron (7.4 per cent Fe_2O_3).

Erämetsä (9) considered the possibility of replacement of ferric iron by gallium, but was unable to test the hypothesis on his samples spectrographically because of line coincidences between the two metals when much iron was present. Tsarovs'kiĭ (11) in studying the gallium content of the minerals of the nepheline pegmatites of the Azov region found the amount of gallium to increase with aluminum in the light-colored minerals and with the sum of aluminum and iron in the dark colored ones.

The ionic radii of trivalent chromium and quadrivalent titanium (each 0.64 A, according to Goldschmidt) are so close to the radius of gallium that the entrance of gallium into the minerals of these elements must be considered a possibility. Goldschmidt and Peters (1) found 5 to 10 p.p.m. of gallium in chromites and 10 p.p.m. in two specimens of magnetite-ilmenite. The aluminum content of these samples is not stated, and it is not known whether gallium shows any enrichment compared to aluminum in them. In ordinary igneous rocks these possible substitutions are of minor quantitative importance. Nockolds and Mitchell (8) found a little gallium in early titanites, but none in the later ones.

The tendency for gallium to be concentrated in alkalic

rocks, as pointed out by Goldschmidt for nephelites, is illustrated by the high gallium content of the pantellerite of Table II. This rock has a gallium-aluminum ratio of almost 10^{-3}. Even the $Ga/(Al + Fe^{III})$ ratio is abnormally high. It seems likely that both gallium and ferric iron have been enriched compared to aluminum because of their greater ionic radii.

Nockolds and Mitchell found the ratio Ga/Al in their rocks (mostly gabbros, diorites and granodiorites) to have the approximate value 2×10^{-4}. Their results are thus much the same as ours, although they report that the ratio remains practically constant throughout the series. However, these authors found Ga/Al to be greater in late than in early hornblendes and biotites. The highest values for the ratio in hornblendes were found in two specimens separated from a tonalite and a granodiorite, which yielded the figures 7×10^{-4} and 8×10^{-4} respectively. In the present work, an alkalic amphibole separated from a New Hampshire granite (12, Table 9), of which it makes up 5 per cent, was found to contain 19 p.p.m of gallium. The Al_2O_3 and Fe_2O_3 content of this amphibole are respectively 2.5 and 7.5 per cent. The ratio Ga/Al is 1.4×10^{-3}. The granite itself was not available for analysis, but it seems unlikely that its Ga/Al ratio would be much greater than 3×10^{-4}, the average for high silica granites.

Nockolds and Mitchell observed that the Ga/Al ratio is lower in early plagioclases than in the later. Their values of the ratio for three plagioclases separated from two gabbros and an appinitic diorite respectively (An = 63, 59, and 45) are slightly greater than 1×10^{-4}, and thus are the same, within the experimental error, as the values obtained for anorthosites (Table II) in the present analyses. In plagioclases of more acid rocks, these authors found Ga/Al to average 3×10^{-4}. It is interesting to note that the ratio is almost uniformly lower (average about 2×10^{-4}) in the potassium feldspars than in plagioclases. Shimer (13) found an average of 40 p.p.m. (from 10 to 60 p.p.m.) of gallium in feldspars separated from New England granites. This content appears to correspond to a Ga/Al ratio somewhat greater than reported by Nockolds and Mitchell for feldspars of the Caledonian rocks.

Abundance of gallium in the lithosphere. The rather monotonous uniformity in the gallium content of most igneous rocks simplifies the problem of obtaining an average value for

gallium in the lithosphere. From the figures in Table I an average of 17 p.p.m. of gallium in granites may be derived. For the common basic rocks a content of 12 p.p.m. may be taken, this average derived from a composite of 24 samples being considered more representative than the other values for basic rocks in the table, although it may be a trifle low. On the assumption that equal weights are to be given to the common basic rocks and to granites in the upper lithosphere, and that the gallium content of intermediate rocks falls between that of these two groups, an average value of 15 p.p.m. is obtained for the gallium content of the earth's crust.

Another method of calculation may be based on the gallium-aluminum ratio of rocks. Taking 2.4×10^{-4} as the average ratio for granites and 1.4×10^{-4} as the average for basic rocks, we obtain a mean of 1.9×10^{-4} which also may be taken to represent the ratio for intermediate rocks. Accepting Clarke's value of 8.1 per cent for the abundance of aluminum in the lithosphere, we arrive at the same figure as before, 15 p.p.m. of gallium. Too much significance should not be attached to this exact value, but it seems unlikely that the abundance is less than 10 p.p.m. or greater than 20 p.p.m. On the basis of 15 p.p.m. of gallium, the atomic ratio of gallium to aluminum in the crusts is 7.5×10^{-5}.

Comparison with previous results. The earlier spectrographic determinations of gallium in silicate rocks and minerals were for the most part semi-quantitative and close agreement with the present results is not to be expected. If this limitation is taken into consideration, our results are substantially the same as those obtained by Goldschmidt and coworkers. Goldschmidt and Peters (1) estimated the average gallium content of granite to be approximately 20 p.p.m. (30 p.p.m. Ga_2O_3), and that of basic plagioclase rocks to be a little less than 10 p.p.m. (10 p.p.m. Ga_2O_3). In a later paper (2) the average 15 p.p.m. of gallium is reported for 14 German granites and slightly less than 10 p.p.m. (10 p.p.m. Ga_2O_3) for 11 German gabbros. For the abundance of gallium in the lithosphere, Goldschmidt (14) arrived at the value 15 p.p.m., the same as calculated above.

Van Tongeren's average for gallium in 49 Dutch East Indies granites of Mesozoic age is 50 p.p.m., with individual values extending from 8 to 375 p.p.m., but mostly in the range

20 to 75 p.p.m. (3, quoted in 15). For gabbros from this region, an average of approximately 40 p.p.m. gallium (50 p.p.m. Ga_2O_3) was found. These amounts are much higher than those found here for American rocks. Rankama (15) is of the opinion that there may be a difference in the gallium contents of pre-Cambrian and younger granites.

In a paper on the trace elements of the rocks of southern Finnish Lapland, Sahama (6) reports an average of approximately 75 p.p.m. gallium for granites and 20-25 p.p.m. (30 p.p.m. Ga_2O_3) for gabbros and dolerites. These spectrographic figures are based on the visual comparison of line intensities and Sahama points out that they should be regarded as giving the order of magnitude and that the results may be in error by the factor 2 or 3. Moreover, he states that further work is likely to lower these values, rather than to raise them. In a standard mixture of East Fennoscandian rapakivi granites, Sahama found approximately 75 p.p.m. of gallium (7).

Rankama (4) obtained results very similar to those of Sahama for gallium, in an earlier study of other Finnish rocks.

Wager and Mitchell (5) give 25 p.p.m. as the gallium content of the olivine-gabbro magma of the Skaergaard intrusion, East Greenland. This value is based on the analysis of the chilled facies of the marginal contact. The gallium concentration of the various rocks of the layered differentiation series was found to vary from 10 to 20 p.p.m., in sympathy with the aluminum content. No trend in the value of the gallium-aluminum ratio is evident, the average value being slightly greater than 2×10^{-4}. Gallium was evidently determined to the nearest 5 p.p.m. These values are not greatly different from those for corresponding basic rocks analyzed here, but they tend to be higher.

In the recent work of Nockolds and Mitchell (8), to which reference has already been made, the gallium content of rocks of western Scotland (mostly gabbros, diorites, and granodiorites) was found to run from 15 to 20 p.p.m., very rarely higher or lower. These results agree with corresponding values in Table I.

On the whole, one obtains the impression of great uniformity in the gallium content of the common igneous rocks, independent of age and locality.

ACKNOWLEDGMENT

The writer is greatly indebted to Prof. F. F. Grout for placing at his disposal rock samples analyzed in the Rock Analysis Laboratory, University of Minnesota; most of the composites were prepared from these, and some of the individual samples analyzed were taken from this collection. He is also indebted to Dr. S. S. Goldich for reading and commenting on the manuscript.

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DENDRASTER ELSMERENSIS DURHAM, N. SP.[1]

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ABSTRACT. The new species, *Dendraster elsmerensis* Durham, with a marginal periproct is described. The plate systems of the oral surface, the internal structure, and the pattern of the ambulacral food grooves of the genera *Anorthoscutum*, *Dendraster*, *Echinarachnius* and *Merriamaster* are described and compared. It is concluded that the four genera are distinct, with *Anorthoscutum* being the most primitive, and the genotype of *Echinarachnius* somewhat advanced, but still more primitive than *Dendraster* and *Merriamaster*. However, the middle Miocene species *E. merriami* is more primitive than any of the other genera and could possibly represent the ancestral stock.

THE occurrence of an echinoid which closely resembles *Dendraster excentricus* (Eschscholtz) in the basal beds of the Pico formation in Elsmere Canyon, near Newhall, California, has long been known (Pack, 1909, p. 282; English, 1914, p. 209; Kew, 1920, p. 122; Woodring, Stewart and Richards, 1940, p. 111). All workers who have recorded their observations have identified the specimens from this locality as *D. excentricus*, and this occurrence of the living species has been cited (Kew, 1924, pp. 79-80) either as indicating a long time range for *D. excentricus*, or else as indicating a later age for the containing beds than lower Pliocene.

The original echinoid material upon which Pack, English, and Kew based their statements is in the University of California collections, locality numbers 1601 and 1602.[2] Examination of the specimens from these localities shows that they rather closely resemble *D. excentricus*, but are all fragmentary and none show the periproct. Recently additional specimens (loc. A 4457) were collected from what is assumed to be near the same locality.[3] and certainly is at the same horizon as the original material.

[1] A contribution from the Museum of Paleontology of the University of California, Berkeley, California.

[2] All locality and specimen numbers used in this paper refer to the Invertebrate Collections, Museum of Paleontology, University of California, Berkeley, California.

[3] Loc. A 4457 — apparently in SW ¼ of NE ¼ of Sec. 8, T 3 N, R 15 W, San Bernardino Base and Meridian. From hillside on northwest side of stream, about 200 yards upstream from point where contact of Pico formation and basement cross the stream. Collected from 0′ to 25′ above base of Pico formation. In association with numerous molluscs and *Astrodapsis fernandoensis* Pack.

Some of the specimens are complete and moderately well preserved. On all individuals (5) in which that part of the test is preserved, it can clearly be seen that the periproct is marginal, a feature which immediately removes this species from the genus *Dendraster*, according to the conventional criteria used by most present day American workers in this field (as exemplified by Grant and Hertlein, 1938, pp. 53, 78). However, in all other respects, the specimens are typically *Dendraster*, and it is worthy of note that Stewart (Woodring, Stewart and Richards, 1940, p. 81) has shown that in *D. coalingensis* Twitchell, the periproct is occasionally marginal or supramarginal. Because of the above anomaly, a review of the allied genera *Echinarachnius*, *Anorthoscutum* and *Merriamaster* was undertaken during the description of the species and it was concluded that the Elsmere Canyon species is a primitive member of the genus *Dendraster*. The description of the new species is as follows:

Genus *Dendraster* Agassiz

Dendraster Agassiz, in Aggasiz and Desor (1847), Ann. Sci. Nat. (Zool.), ser. 3, vol. 7, p. 135; Grant and Hertlein (1938), Univ. Calif. Los Angeles, Publ. Math. Phys. Sci., vol. 2, pp. 78-79.

Dendraster elsmerensis Durham, n. sp.

Pl. 1, figs. 2, 3, 4, 6; Text-fig. 2F

Echinarachnius excentricus Esch., English (1914), Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 8, p. 209.

Dendraster excentricus (Eschscholtz), Kew (1920), Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 12, pp. 121-122, *partim* (lower Pliocene occurrence only).

Dendraster excentricus Eschscholtz, Grant and Hertlein (1938), Univ. Calif. Los Angeles, Publ. Math. and Phys. Sci., vol. 2, pp. 84-87, *partim* (lower Pliocene occurrence only).

Test moderately small, margins thin, apical system moderately excentric, periproct marginal; in general appearance quite similar to *D. excentricus* except for its smaller size and marginal periproct; center of apical system about two-thirds the length of test from anterior margin; test variable in outline, from elongate ovate to shortened ovate; length of right petal of trivium slightly over two-thirds the radius of test from

center of apical system (three specimens), as compared to slightly under two-thirds for the corresponding radius of *excentricus*; length of anterior petal of trivium between two thirds and three-fourths of the corresponding radius, as compared to about three-fifths for *excentricus*; angle between the bivium less than in *excentricus* or *gibbsii*, and about the same as in *vizcainoensis*; peristome 0.42 to 0.45 length of test from posterior margin; about ten tubercles across middle of anterior petal between pores, compared to about sixteen in a similar position for *excentricus*, and four or five for a new species from the Pliocene of the Gulf of California area; internal supporting walls and pillars of test fewer than in *excentricus*, being about comparable to those of *Echinarachnius parma*; primordial ambulacral and interambulacral plates both present in basicoronal row, both moderately small, but with interambulacral plates larger than ambulacral (text fig. 2F), only ambulacral plates present in penultimate row; auricles slightly oral from center of interambulacral plates, character not specifically determinable but apparently similar to *excentricus*; pattern of ambulacral and interambulacral plates on oral surface generally similar to that of *excentricus* except that there are fewer ambulacral plates between the ends of the petals and the ambitus, whereas the number of interambulacral plates is approximately the same.

Dimensions: holotype no. 32949, length 43 mm., width (incomplete) 44 mm., height 7.3 mm.; paratype no. 32950, length 34 mm., width (incomplete) 33 mm., height 5.5 mm.; paratype no. 32956, length (incomplete, estimated) 37 mm., width (incomplete, estimated) 39 mm.

Types: holotype no. 32949; paratypes nos. 32950, 32951, 32956, 32957; all specimens from loc. A 4457; paratype 32953 from loc. 1602. Two paratypes deposited in Paleontological collections of the California Academy of Sciences, San Francisco.

Age: The associated fauna has been commonly considered as of lower Pliocene age.

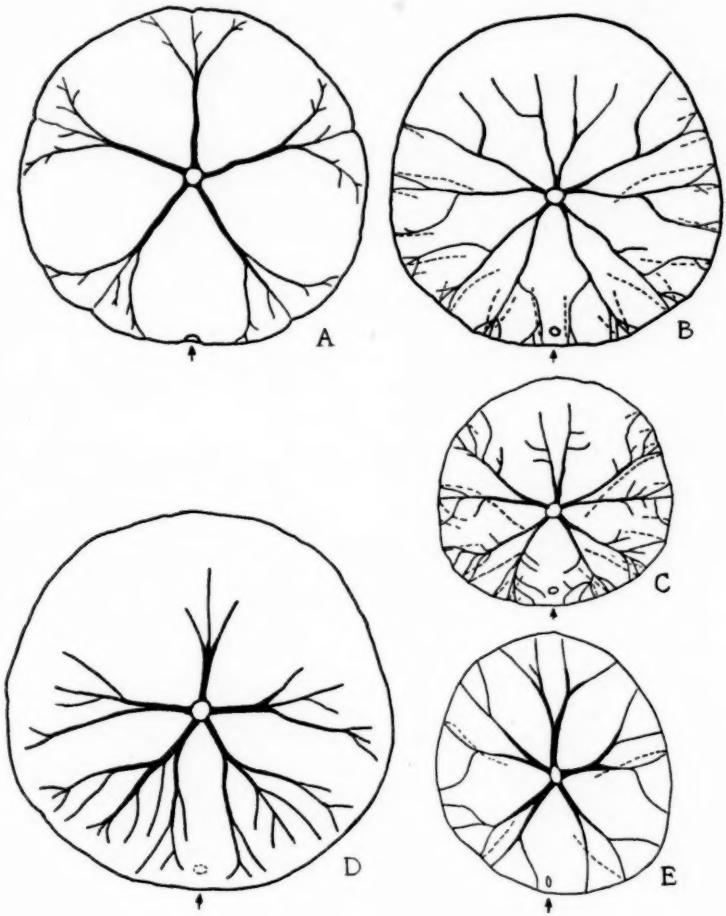
Discussion.—The marginal periproct separates this species from all known species of *Dendraster*. Superficially except for the position of the periproct it is quite similar to *D. excentricus*. However, the fewer number of tubercles across the width of the anterior petal readily separate the two, and the lesser

angle between the bivium is also characteristic. Internally the species is readily separable from *D. excentricus* by the relatively few internal supporting walls and pillars—being closely similar to *Echinarachnius parma* (pl. 1, fig. 8) in abundance and pattern. Possibly it may have even fewer concentric pillars than that species. Sections of *D. excentricus* (pl. 2, fig. 4), *D. gibbsii* (Remond) (pl. 2, fig. 2), *D. coalingensis* Twitchell (pl. 2, fig. 1) and a new species from the Pliocene of the Gulf of California area have been made and compared with the present species. All except *D. gibbsii* are closely similar to *excentricus* rather than to *elsmerensis*, possibly an indication of a primitive trait in the last named form. *D. gibbsii* differs from all other species investigated in the markedly heavy character of the partitions and pillars. The pattern of the food grooves on the oral surface of *elsmerensis* is not readily discernible, but on paratype no. 32953, part of it can be faintly seen and appears to be similar to that of *D. excentricus*.

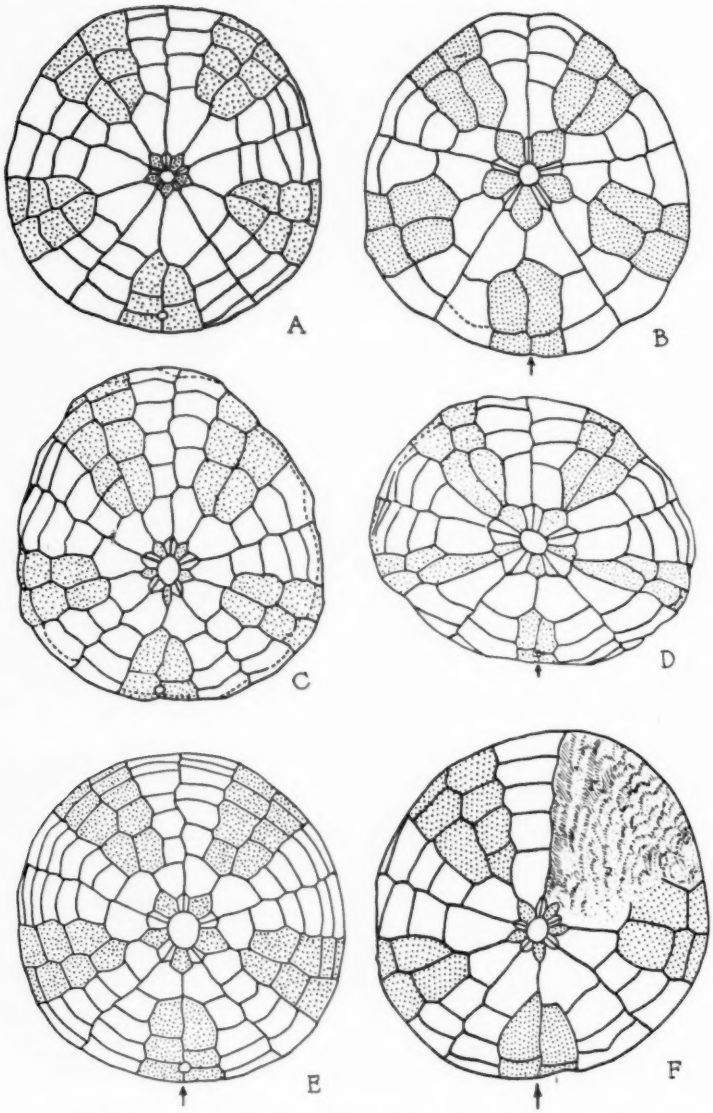
The non-conformity of the periproct of *D. elsmerensis* to the conventional criteria of the genus *Dendraster* led to an investigation of the pattern of the ambulacral grooves, the internal structure, and the plate systems of the Pacific Coast genera *Anorthoscutum*, *Dendraster*, *Echinarachnius* and *Merriamaster* as members of an apparently closely related group. Specimens of the genotypes and other species of each of the genera except *Anorthoscutum* were sectioned and examined by various means. No well-preserved specimens of the type of *Anorthoscutum* (*Scutella interlineatum* Stimpson) were available for preparation, but specimens of *A. oregonense major* and *A. oregonense quaylei*, both closely related to the type, were utilized. Available specimens of *Anorthoscutum interlineatum* were adequate to show that they have the same arrangement of the plates on the oral side of the test as *A. oregonense quaylei*. Because all other characters are similar, it has been assumed that the pattern of the ambulacral grooves is basically the same as in *A. oregonense major*, the species of this genus in which they have been observed.

Text figure 1 illustrates the pattern of the ambulacral grooves on the oral surface of the above genera. It is readily seen that there are four principal types—corresponding to the four genera, with that of *Echinarachnius* being markedly different from the rest in that each ambulacral unit is nearly

symmetrical with the others. The pattern of *Echinarachnius parma* also differs from that of the other genera in that the



Text fig. 1. Pattern of ambulacral grooves on oral surface (dotted lines indicate continuation on aboral surface): A, *Echinarachnius parma* Lamarck) (XO.7), hypotype no. 32933 (loc. A 4455); B, *Dendraster excentricus* (*Eschscholtz*) (XO.7), hypotype no. 32934 (loc. A 3783); C, *Dendraster gibbsii* (Remond) (XO. 7), hypotype no. 32940 (loc. A 4321); D, *Anorthoscutum oregonense major* (Kew) (XO.7), cotype no. 11352 (loc. 71); E, *Merriamaster perrini* (Weaver) (XO. 7), hypotype no. 11062 ("Coalinga District"). (Arrow indicates periproct on all figures.)



Text fig. 2. A, *Dendraster excentricus* (Eschscholtz) (XO.75), hypotype no. 32958 (loc. A 3783). Plate system on oral surface (interambulacral plates stippled); B, *Echinarachnius parma* (Lamarck) (X 1), hypotype no. 32931 (loc. A 4456). Plate system on oral surface (interambulacral

grooves do not branch until over halfway to the margin where the main groove gives off two lateral branches of approximately equal size, then all three continue to the margin with a few short minor branches on each main branch.

The genus *Merriamaster* as represented by the genotype, *M. perrini*, also appears to have nearly symmetrical branching on the oral surface, and is usually considered to have the grooves restricted to the oral surface (Grant and Hertlein, 1938, p. 53, key), and on most specimens such is apparently the case. However, a single large (length 51.5 mm.) well-preserved specimen (text fig. 1-E) (hypotype no. 11062, "Coalinga District") clearly shows faint extensions of the grooves onto the oral surface in all except the anterior ambulacrum. This same specimen also shows secondary branching on the oral surface near the margin, in contrast to the simple furrows shown by Stewart (Woodring, Stewart and Richards, 1940, pl. 46, figs. 1, 2). However, his specimens are much smaller than the one here noted, and inasmuch as all other specimens available to the present author (mostly of the same size as Stewart's) show the same type branching as his, it may be possible that the more complex branching does not begin until large size is attained (and can only be observed on well-preserved specimens). The extension of the grooves onto the oral surface is a feature in common with *Dendraster*, but the entire system is much less complex than that of that genus (see text fig. 1-B, C). A further difference between the two genera is in the greater development of the grooves of the anterior ambulacrum of *Merriamaster*.

The ambulacral grooves of the genus *Anorthoscutum* as typified by those of *A. oregonense major* (text fig. 1-D) are somewhat similar to those of *Dendraster* in that the system of the two posterior ambulacra is the most complex, while that of the anterior ambulacrum is the most reduced. However,

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plates stippled, arrow indicates periproct); C, *Dendraster gibbsii* (Remond) (X1.5), hypotype no. 32941 (loc. A 4321). Plate system on oral surface (interambulacral plates stippled); D, *Anorthoscutum oregonense quaylei* Grant and Hertlein (X1.5), topotype no. 32943 (loc. 1881). Plate system on oral surface (interambulacral plates stippled, arrow indicates periproct); E, *Merriamaster perrini* (Weaver) (X1.9), hypotype no. 32948 (loc. A 4320). Plate system on oral surface (interambulacral plates stippled); F, *Dendraster elsmerensis* Durham, n. sp. (X1.5), paratype no. 32950 (loc. A 4457). Plate system on oral surface (interambulacral plates stippled, arrow indicates position of periproct).

there is no evidence of any extensions on the aboral surface, and the branching is usually a modified trifurcation instead of a bifurcation. Further, the main branching takes place at a point about one-third out from the peristome instead of very close to it.

The basic pattern of the ambulacral grooves appears to be much the same in all species of *Dendraster* examined, with the greatest differences being found in *D. gibbsii* (text fig. 1-C) as contrasted with *D. excentricus* (text fig. 1-B). As in *Anorthoscutum*, the system of the anterior ambulacrum is the simplest, while those of the two posterior areas extend over the margin onto the aboral surface. Generally each ambulacral groove bifurcates once close to the peristome, and a second time, somewhat unequally, about a half or two-thirds the distance to the margin, and subsequently several short minor branches are given off. *D. gibbsii* differs from *D. excentricus* in that the minor branches are more numerous and that the second bifurcation does not differ greatly in prominence from the subsequent minor branches.

In the ambulacral and interambulacral plate systems (text fig. 2) of the oral side of the test, marked differences are apparent between some of these genera and close similarities between others. The arrangement of the plates in *Merriamaster* and *Dendraster* is quite similar, but *Echinarachnius* and *Anorthoscutum* are markedly different from each other and from the other two. The plates of the basicoronal row surrounding the peristome in each case consists of ten ambulacrals and five interambulacrals, thus conforming to the typical clypeastroid pattern of the suborder (Jackson, 1912, pp. 71, 72, text fig. 52). Comparatively speaking, the plates of the basicoronal row

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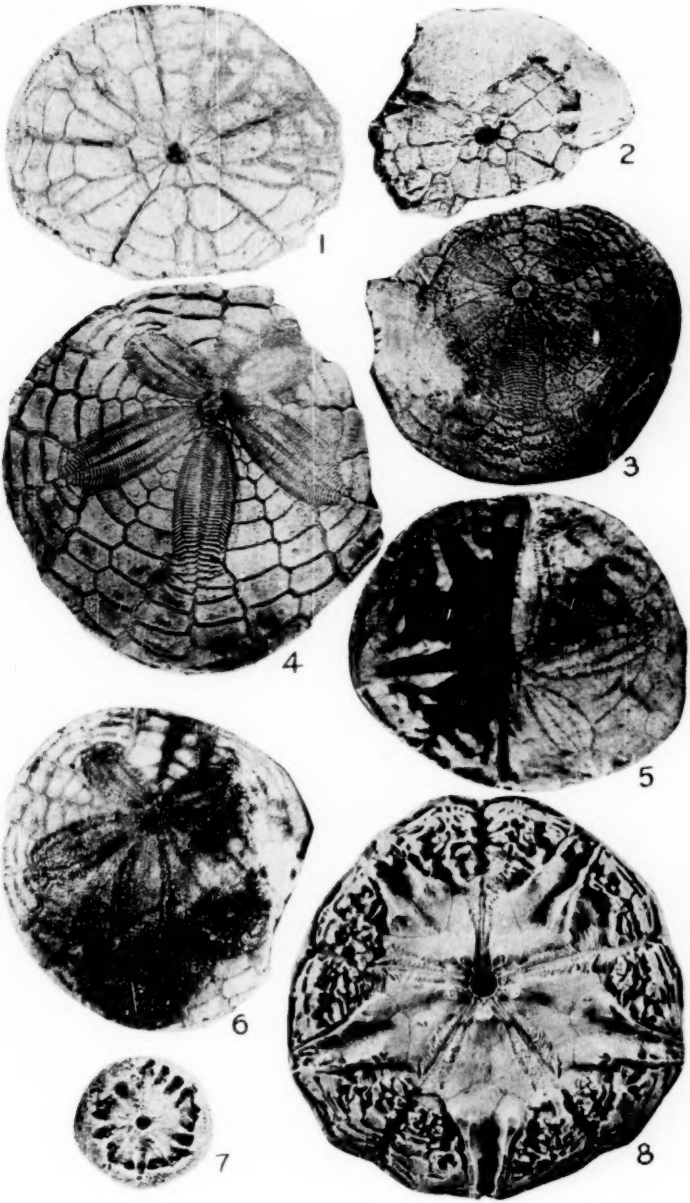
PLATE 1.

1. *Anorthoscutum oregonense quaylei* Grant and Hertlein (XI.4), topotype no. 32943 (loc. 1881). Oral surface.

2, 3, 4, 6. *Dendraster elsmerensis* Durham, n. sp. 2.—(XI.2), paratype no. 32957 (loc. A 4457), natural section, internal view of plates surrounding mouth; 3.—(XI.1), aboral view of paratype no. 32956 (loc. A 4457); 4.—(XI.25), holotype no. 32948 (loc. A 4457); 6.—(XI.25), paratype no. 32950 (loc. A 4457)—note tubercles in anterior ambulacrum

5. *Anorthoscutum oregonense quaylei* Grant and Hertlein (XI.4), holotype no. 32944 (loc. 1883). Partial section to show internal partitions.

7. *Anorthoscutum* sp. (XI.25), hypotype no. 32942 (loc. A 3779). Partial section of a small specimen to show internal partitions and position of auricles.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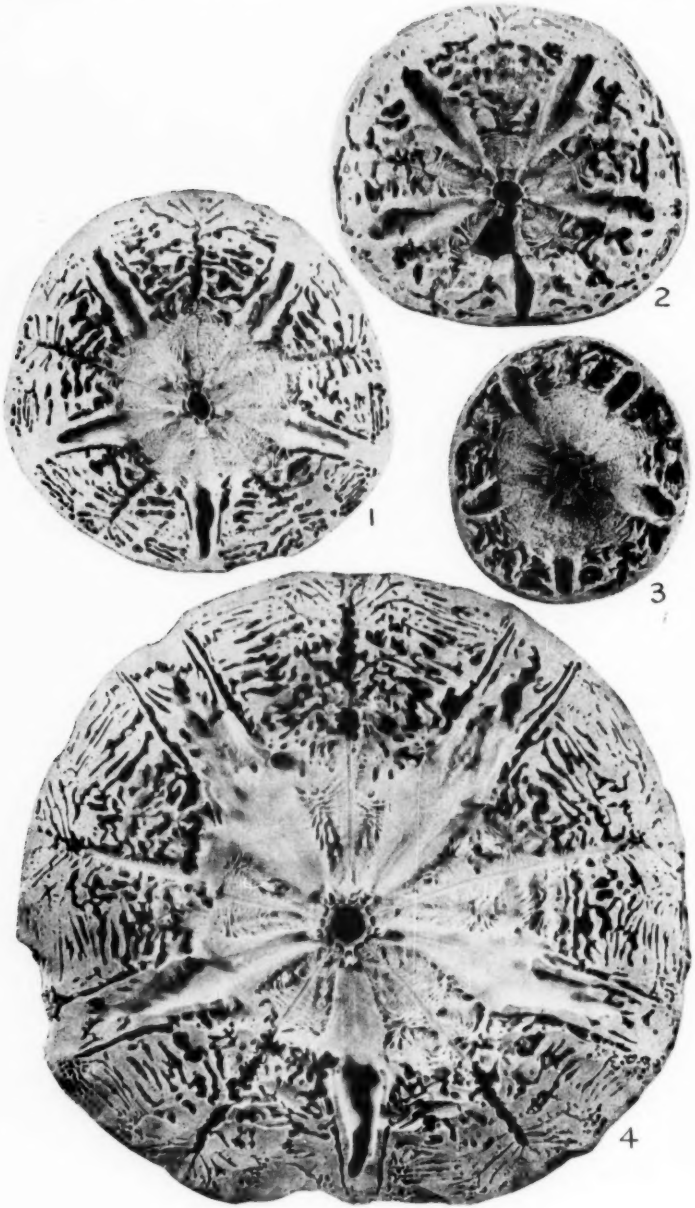
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are smallest in *Dendraster*, and successively larger in *Merriamaster*, *Anorthoscutum*, and *Echinarachnius*.

On the basis of the arrangement of the plates, *Anorthoscutum* (text fig. 2-D) appears to be the most primitive genus in that the interambulacral plates of the basicoronal row are in contact with subsequent plates of the interambulacrum in areas 1, 2, 3 and 4, and only in area 5 have the interambulacral plates been pushed dorsally so that the first postprimordial ambulacral plates of areas I and V are in contact. In interambulacral areas 1 and 4, only one column of plates is in contact with the primordial plate, with the plate making this contact being very high and rather narrow. In areas 2 and 3, both columns make contact with the basicoronal plate. The plates of the basicoronal row are moderately large and the interambulacral plates in areas 2 and 3 are larger than the other three. On the oral surface, there are from three to six post basicoronal rows of plates in each ambulacral column. In the interambulacral areas, there are two post basicoronal plates to a column in area 5, two in the anterior and three in the posterior columns of areas 1 and 4, two in the posterior and three in the anterior columns of areas 2 and 3. The interambulacral plates of the basicoronal row are from one to three times as large as the adjacent ambulacrals.

In *Echinarachnius* (text fig. 2-B), in contrast to *Anorthoscutum*, the interambulacral plates of the basicoronal row are just barely in contact in areas 2 and 3 with the succeeding plate of the columns and are completely separated from them in areas 1, 4 and 5. The primordial interambulacral plates of the basicoronal row have become greatly enlarged in contrast to the adjacent primordial ambulacrals and have a total area six to eight times as great. There are three to four postbasicoronal plates in each ambulacral column on the oral surface, but only two interambulacral plates to a column. The

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PLATE 2

1. *Dendraster coalingensis* Twitchell (X1.25), hypotype no. 32938 (loc. A 3346). Internal view of sectioned specimen.
2. *Dendraster gibbsii* (Remond) (X1.25), hypotype no. 32939 (loc. A 4321). Internal view of sectioned specimen.
3. *Merriamaster perrini* (Weaver) (X1.25), hypotype no. 32947 (loc. A 4320). Internal view of sectioned specimen.
4. *Dendraster excentricus* (Eschscholtz) (X1.25), hypotype no. 32935 (California). Internal view of sectioned specimen.

shape of the primordial interambulacral plates is considerably different than that shown by Jackson (1912, p. 80, fig. 52) for a specimen of the same species from Eastport, Maine. The specimen here studied is from Kodiak Island, Alaska. The marked differences between the shape of these particular plates indicate that specimens of this species (*Echinarachnius parma*) from all parts of its range should be carefully studied to see if there may not be some geographic differentiation present.

Dendraster (text fig. 2-A, D, F), *Merriamaster* (text fig. 2-E), and *Astrodapsis* (not figured) are characterized by the plates of the basicoronal row being quite small in comparison to the next row of plates, and by all the interambulacral areas being approximately equally separated from the basicoronal interambulacral plates, so that the first row of post-basicoronal ambulacral plates of each ambulacrum is in lateral contact with the plates of the adjacent ambulacrum. In addition, in contrast to the condition prevailing in *Echinarachnius* but similar to that in *Anorthoscutum*, the first post-basicoronal ambulacral plates are considerably larger than subsequent plates of the same column. In *Dendraster excentricus* (text fig. 2-A), there are three to four (except area 5 which has two) post-basicoronal plates in each interambulacral column, and one large and three to four smaller plates in each ambulacral column on the oral surface. *D. gibbsii* (text fig. 2-C) is similar except that there may be an extra plate in each column of the anterior areas and only two in each column of interambulacrum 5—a feature caused by the greater excentricity of this species. The new species, *D. elsmerensis*, is generally similar to *D. excentricus*.

In *Merriamaster*, the arrangement of the plates is quite similar to *Dendraster* except that the basicoronal plates are proportionately a little larger, and that there are more plates in the columns on the oral side and the individual plates near the ambitus have a very low altitude in proportion to their length, a character in which they are allied to *Astrodapsis*. In the ambulacral areas, there is one large post-basicoronal plate followed by four to six plates in a column, with the most plates in the anterior areas, while there are three to five post-basicoronal plates in the columns of the interambulacral areas, again with the most plates in the anterior areas.

The internal partitions and buttresses of the four genera

are shown on plate 1, figs. 5, 7, 8 and on plate 2, figs. 1-4. All the genera are typified by two fairly closely spaced radial partitions extending from the periphery inwards some distance in each interambulacrum, together with a variable development of supplementary concentric buttresses. Those of *Merriamaster* (pl. 2, fig. 3) are the simplest, extending in only about one-third of the distance from the periphery and having only a slight development of supplementary buttresses, this latter fact separates it from *Astrodapsis*, which in the species examined (no members of *A. whitneyi* stock) has no supplementary buttresses. *Anorthoscutum* (pl. 1, figs. 5, 7) has the radial partitions and buttresses about equivalent to *Merriamaster* but much heavier. *Echinarachnius* (pl. 1, fig. 8) has the same radial partitions, and finer but more abundant buttresses covering a greater area of the floor, but not as many as in all of the Dendrasters examined except *D. elsmerensis*. Typical *Dendraster* (pl. 2, figs. 1, 4) has exceedingly abundant buttresses but *D. gibbsii* has fewer but exceedingly heavy buttresses covering nearly as much area as those of the typical species.

For comparison with the preceding genera, specimens of *Astrodapsis arnoldi* var., *Echinarachnius gabbii* (Rémond), *E. merriami* (Anderson), *E. gabbii kleinpelli* Grant and Hertlein (*Scutella gabbii* var. *tenuis* Kew), *E. vaquerosensis* (Kew), and *Eoscutella coosensis* (Kew) were examined.

Astrodapsis is readily separable from the genera previously discussed in this paper by the numerous low plates of the ambulacral columns outside of the petals extending over the ambitus onto the oral surface before they begin to increase in size, in addition to having raised petals, and ambulacral grooves on the oral surface of the general type of *Echinarachnius parma*. In the arrangement of the plates, the internal partitions, and the slightly raised petals, *Merriamaster* appears to be much closer to *Astrodapsis* than to *Dendraster* where *Stewart* (Woodring, Stewart and Richards, 1940, p. 81) placed it.

Echinarachnius vaquerosensis has rather large postbasicoronal plates in contact with the basicoronal interambulacral plates only in areas 2 and 3, in much the same manner as *E. parma*. The pattern of the ambulacral grooves cannot be made out, but the species, except for its laterally elongated shape, appears to be well placed in this genus. In

E. gabbii, the post-basicoronal interambulacral plates are in contact with the basicoronal row in each area except 5, but the basicoronal plates are rather large, and several ambulacral plates of very low altitude in comparison to their width are present on the oral surface. The first post-basicoronal interambulacral plates are somewhat elongated, and it is possible that it may be near the ancestral stock of *Anorthoscutum*, but certainly this species is not in the direct line for it has too many plates in the ambulacral columns outside of the petals. It may also be a side branch of the stock that produced *Astrodapsis*. Certainly it is not a typical *Echinarachnius*, although Nisiyama (1940, p. 817) included it within the typical subgenus.

In *Echinarachnius gabbii kleinpelli* (hypotype no. 11370), the basicoronal plates are moderately large and the post-basicoronal plates in interambulacral areas 2 and 3 are closer (just slightly separated) to the basicoronal plates than those of the other areas, indicating that it is apparently the start of a side branch of the main *Echinarachnius* stock. It is possible that it could be the ancestral radicle of *Dendraster*, which by further separation of the interambulacral plates in areas 2 and 3, slight reduction in size of the basicoronal plates, coupled with a posterior movement of the center of the apical system, evolved into the typical *Dendraster*. Unfortunately the pattern of the ambulacral grooves in this species is unknown. It cannot be closely related to *E. gabbii* because it lacks the numerous small ambulacral plates in the areas outside the petals and therefore should be known as *E. kleinpelli*, not *E. gabbii kleinpelli*.

Echinarachnius merriami (hypotype no. 32984) has rather large plates in the basicoronal row, and the tip of the primordial basicoronal interambulacral plates just touching the tip of subsequent plates in each area except 5. Unfortunately the available specimens of *E. merriami* are not adequate for complete description of the plate systems, but it appears possible that it could be ancestral to all later scutellids discussed in this paper. Nisiyama (1940, p. 816) places this species in his subgenus *Kewia* which he considers the ancestral radicle of the Echinarachnid echinoids.

With regard to the anomalous position of the periproct in *Dendraster elsmerensis*, and that noted by Stewart (Wood-

ring, Stewart and Richards, 1940, pp. 81, 83) for the "small variety" specimens of *D. coalingensis*, it is not nearly as anomalous as might be supposed. The very young of all Scutellids have the periproct either marginal or on the aboral surface. Young *Echinarachnius parma* continue to have the periproct on the aboral surface until a diameter of about 15 mm. (Agassiz, 1870, pt. II, pl. 12, fig. 13). At a diameter of 10 mm., young *D. excentricus* have the periproct just slightly submarginal, and at a diameter of 4 mm., it is marginal. It may be assumed, therefore, that *D. elsmerensis* is primitive in the position of the periproct, while the occasional specimens of *D. coalingensis* mentioned by Stewart are merely individuals in which the migration of the periproct to the oral surface has been retarded.

In summary of the above discussion, it is clearly apparent that *Anorthoscutum* is not as closely related to *Echinarachnius* as was suggested by Stewart (Woodring, Stewart and Richards, 1940, p. 83), and that both genera are distinct from *Dendraster*, although an upper Miocene species of *Echinarachnius*, *E. kleinpelli*, could have given rise to *Denraster*. *Merriamaster* probably is not as closely related to *Dendraster* as it is to *Astrodapsis*.

The genus *Dendraster* may be considered as characterized by an excentric apical system, small plates in the basicoronal row, post-basicoronal interambulacral plates not in contact with basicoronal plates, periproct usually on oral surface, and unequal bifurcating ambulacral furrows extending onto aboral surface in posterior areas. *Echinarachnius* is characterized by a normally central apical system, very large plates in basicoronal row, in advanced species with interambulacral plates in areas 2 and 3 just barely in contact with basicoronal row, but in primitive species, areas 1 to 4 may be in contact with basicoronal row, ambulacral furrows simple, trifurcating near margin and all equal, periproct usually marginal. In *Anorthoscutum*, as far as known, the periproct is always supramarginal, the apical system is usually somewhat excentric, the ambulacral furrows approach those of *Dendraster* in complexity, but the major branching is a modified trifurcation instead of bifurcation. *Merriamaster* is intermediate between *Dendraster* and *Astrodapsis*, having small plates in the basicoronal row, the post-basicoronal interambulacral plates

separated from the basicoronal plates, a rounded margin, submarginal periproct, a few internal buttresses, and simple branching ambulacral furrows which may extend onto the aboral surface.

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DISCUSSION

NATIONAL RESEARCH COUNCIL COMMITTEE ON THE INTERRELATIONS OF PLEISTOCENE RESEARCH

For some time, research workers in such fields as prehistoric archeology, climatology, oceanography, ecology, pedology, as well as certain branches of geology, have been aware of their need for a knowledge of recent progress in each of the other fields so closely allied to their own. The common ground for all is a broad knowledge of Pleistocene history. But as each of the sciences has its own mode of approach, its contributions have remained largely unknown outside its own field. To provide the much-needed coordination and intercommunication, the National Research Council established in June, 1947, a Committee on the Interrelations of Pleistocene Research under the chairmanship of Professor Richard Foster Flint of Yale University. The other members of the committee are: Edward S. Deevy, Jr. (biogeography) Department of Biology, Yale University; Loren D. Eisley (anthropology and new-world archeology), Department of Anthropology, University of Pennsylvania; Claude W. Hibbard (vertebrate paleontology), Museum of Paleontology, University of Michigan; Chauncey D. Holmes (glacial erosion and sedimentation), Department of Geology, University of Missouri; Helmut E. Landsberg (meteorology and climatology), Committee on Geophysical Sciences, Research and Development Board, Washington, D. C.; Hallam L. Movius, Jr. (old-world archeology), Peabody Museum of Archeology and Ethnology, Harvard University; Fred B. Phleger, Jr. (oceanography and sea-floor geology), Department of Geology, Amherst College; Louis L. Ray (glacial stratigraphy; alpine glacial geology), U. S. Geological Survey, Washington, D. C.; H. T. U. Smith (eolian features; frozen ground; stream terraces), Department of Geology, University of Kansas; and James Thorp (soil science), Division of Soil Survey, U. S. Department of Agriculture, Lincoln, Nebraska.

Individual preliminary work was begun as soon as the committee was authorized, and on April 5 and 6 the committee held its first meeting. The results are most gratifying. In following out the program planned at that time, the committee invites suggestions and assistance from all scientists interested in problems of the Pleistocene. Correspondence should be directed to the individual member representing the particular field, or to the chairman.

CHAUNCEY D. HOLMES

DEPARTMENT OF GEOLOGY
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REVIEWS

Atomic Energy, being the Norman Wait Harris Lectures delivered at Northwestern University by KARL K. DARROW, Ph.D. Bell Telephone Laboratories. Pp. 80. New York, John Wiley and Sons, London, Chapman and Hall, 1948, $2.00.—The requirement that a series of lectures be published sometimes ruins them for their audiences, as it is an excuse for the speaker to read a book supporting or advancing his reputation for originality. In the present case the lecturer was too honest to make hay in this manner while his hearers slept. It is even probable that he was as much enjoyed by those present as he will be by the "layman" to whom he hesitantly addresses his preface.

The physicist, who is not particularly invited to read this little book, will find nothing in it to offend his critical eye except the statement that 1913 was the year in which the existence of isotopes with different masses was established. It is literally correct, but the idea of isotopes came six years earlier with the announcement by Boltwood of the discovery of ionium. A chemist may, and should, object to the statement that hydrogen is explosive. (Even its "demassing" into helium is a slow process.) All experimentalists will be slightly shocked, as was this reviewer, by the author's relative neglect of the techniques in nuclear physics. A wave of the hand to a Van de Graaf machine, a few nods to C.T.R. Wilson's cloud chamber, and an oblique glance at scintillation counting are about all that can be found before the moderation of a nuclear reactor is described. The zealot for one world or none, who frequently does not make it too clear which horn of this dilemma he prefers to be impaled upon, will not like this book because it does not spend many words on *The Bomb*, and perhaps, relies too much upon the dubious emphasis of understatement (p. 61). The intelligent man who can appreciate quantitative reasoning will find this a pleasant way to find out *where* the fantastic energies of nuclear reactions arise, and if he doesn't quite see *how* mass is turned into kinetic energy he can comfort himself by learning here that nobody is yet appreciably wiser on this point. L. W. MCKEEHAN

Electrical Measurements in Theory and Application; by ARTHUR WHITMORE SMITH. Fourth Ed. New York, Toronto, London, 1948 (McGraw Hill Book Co., $4.25).—The first edition, entitled Principles of Electrical Measurements, appeared in 1914, and already was backed by ten years of personal experience. Throughout the series the author has included relatively lengthy discussions of the units in which results of measurement are obtained. The theory of measurement, in any more fundamental sense, is not considered,

and the inclusion of the word "theory" in the title is therefore somewhat misleading. It is also confusing that the author elects to begin building up the practical system of units with the law of force between current elements, so that, as compared with more usual procedures, the definitions given as basic are strikingly arbitrary in appearance. Perhaps the most disturbing change since the third edition, of 1934, is the adoption of the half-baked notion, introduced into quick courses for electronics technicians during World War II, that because electrons almost visibly flow in some circuit elements, the positive direction of electric current must be inverted from its classical sense to follow the motion of negative electricity. This is not to be accepted on any less authority than that of an international convention and is especially unattractive at a time when the motions of positively charged particles are being so extensively studied.

The descriptions of experiments are painstakingly complete, and the book will be found a satisfactory laboratory manual where direct current and low-frequency measurements are to be emphasized. The amount of space devoted to high frequency electrical measurements and to modern electronic devices, is trivial. (The cathode-ray oscilloscope, and the electron-tube amplifier, are brushed off in a total of two pages, and electrical counting is not even mentioned.)

The circuit diagrams (except for arrows pointing up potential gradients) are good. Other illustrations, especially half-tones from advertising brochures, are less useful. Paper and printing are excellent. L. W. MCKEEHAN

Very High Frequency Techniques, Volumes I and II; by THE STAFF OF THE RADIO RESEARCH LABORATORY, HARVARD UNIVERSITY. Pp. 1059; 923 Figs. New York, 1947 (McGraw Hill Book Co., $14.00).—The two volumes contain over one thousand pages, with nearly one thousand illustrations, divided into thirty-five chapters. The table of contents indicate that thirty to forty authors had some part in the production of the publication, and most of these people have already demonstrated their ability in previous publications. Under the able editorial direction of Dr. Herbert J. Reich they have produced an amazingly concise, yet complete, reference on the work done by the staff of the Radio Research Laboratory during the war years. The illustrations are, for the greater part, line drawings that serve to illustrate important features better than photographs, in that interiors can be indicated.

Antennas and microwave tubes are emphasized in these volumes with special emphasis on the development of the resnatron and on the characteristics of certain types of magnetrons. An outline of

the method of measurement is given in nearly every instance of supplied data, enabling the reader to qualify the data to his own satisfaction. In addition to the large amount of data on characteristic types, theoretical information is also supplied. The section on impedance matching and broadbanding (Chapter 3) is typical of the clear presentation of rather difficult concepts encountered throughout both books.

A bibliography is supplied in supplementary form. It is quite complete, but of necessity bears upon technical reports that may not be readily available.

These books should be of value as a text in advanced high-frequency classes and as references for research and development workers already established in the field. WILLIAM L. BRISCOE

Heat Conduction, with Engineering and Geological Applications; by LEONARD R. INGERSOLL, OTTO J. ZOBEL and ALFRED C. INGERSOLL. Pp. viii, 278; 43 figs. New York, 1948 (McGraw-Hill Book Co., Inc., $4.00).—This is a thorough revision and amplification of the text by Ingersoll and Zobel first published in 1913. The basic mathematical theory of heat conduction, dating back to Fourier, is presented in some detail. For those whose interests are largely on the practical side there is a valuable chapter on auxiliary graphical and other approximation methods for solving heat conduction problems with only the simplest mathematics. These procedures are often of sufficient accuracy for practical purposes, and provide solutions for many problems too complex to be treated by rigorous classical methods. Only a reasonable knowledge of calculus is necessary for reading this book.

Geologists, geographers and engineers will find discussions of many applications of heat conduction in their fields. References to the literature are numerous and up-to-date. This is definitely an authoritative book on heat conduction, of value both to students of mathematical physics and to all scientists who need these methods in the solution of their practical problems. W. W. WATSON

General Chemistry; by FRANCIS E. RAY. Pp. viii, 592; 183 figs. Chicago, 1947 (J. B. Lippincott Co., $4.50).—At the occasional risk of the contempt of students for the too familiar, this book brings chemistry very much to life for the beginner. Elementary enough in its approach for nearly any freshman course, it nevertheless contains enough new material to hold the interest even of students for whom most of the material will be in the nature of review.

The language is refreshingly simple, with none of the much-too-common flights of pedagogical verbosity. There is an inquisitive

attitude in the introductions to principles which is bound to stimulate interest. The author's practice of sketchily covering historical matter and carrying this up to hints of present boundaries of knowledge will have a similar effect.

In describing processes of chemical manufacture, the underlying principles are usually mentioned in the opening sentence rather than vaguely referred to at haphazard points in the description. Further, up-to-date processes are described with an ample supply of recent photographs and diagrams. ELLIOT PIERCE

Organic Chemistry; by FRANCIS E. RAY. Pp. x, 750. Chicago, 1947 (Lippincott Co., $4.50).—The author's stated purpose is to bridge the gap between text book and current literature. Though his efforts in this direction are heroic, it is as difficult a task for a one-volume elementary text as for a one-year elementary course. Actually, while falling short of this goal, he has produced an excellent text for an organic course for pre-medical students or for an introductory course for chemists.

The book is divided up according to classes of compounds, broken down as far as possible. A summary of synthetic methods appears near the end of each chapter. A unique feature is the use early in the book of photographs of molecular models. This should encourage early comprehension of three dimensional molecules. It should also suggest to instructors the value of using molecular models in class. Properties of compounds are tabulated more frequently and more plainly than in most texts, another useful feature.

ELLIOT PIERCE

Frontiers in Chemistry. Vol. V. Chemical Architecture; by R. E. BURK and OLIVER GRUMMITT. New York, 1948 (Interscience Publishers, Inc., $4.50).—The nature of *Frontiers in Chemistry* has been discussed before in these columns. Volume V of the series is a particularly important and interesting contribution, containing as it does a collection of highly authoritative discussions of molecular structure. The authors of the articles are, as usual, well known workers in their fields. The contents are as follows:

Hugh S. Taylor: *Applications of Molecular Geometry in the Field of Reaction Mechanism.*
Charles P. Smyth: *Dipole Moment, Resonance and Molecular Structure.*
W. Conrad Fernelius: *Structure of Coordination Compounds.*
B. E. Warren: *X-Ray Studies of Randomness in Various Materials.*
H. Mark: *Light Scattering in Polymer Solutions.*
Miroslav W. Tamele: *The Nature of Inorganic Gels.*

The discussions themselves, particularly in view of the excellent bibliographies appended to each, might well serve as a text for a large section of a graduate course in general chemistry. Any chemist will find this volume interesting, informative, and useful.

HENRY C. THOMAS

A Textbook of Geomorphology; by PHILIP G. WORCESTER. Pp. vii, 584; 385 figs. New York, 1948 (D. Van Nostrand Company, Inc., $5.25).—This second edition of Worcester's textbook is little changed from his first edition. The most notable addition, which will be of considerable help in teaching, is the lists of topographic maps at the end of eight of his nine chapters dealing with topography of land forms. Recent publications added bring the reference lists at the end of the chapters up to date. The chapter "Materials of the Lithosphere. Elements and Minerals." in the first edition now has been reduced to an appendix. This appropriately might have been done to the chapter "Materials of the Lithosphere. Rocks." The section on Characteristics of Streams, which includes descriptions of the types of streams, such as consequent, subsequent, obsequent, insequent, antecedent, and superimposed streams (pp. 146-149), is still the best of its kind found in Geomorphology textbooks. In the chapter "Shore Forms and Shore Processes of Seas and Lakes," a new section on Rip Currents (p. 381) has appeared in place of a paragraph on Rip Tides and Rip Currents, with a new diagram (fig. 265) to illustrate. There are new photographs, two of which are oblique aerial photographs (figs. 339 and 341) of a coral atoll and a volcanic island with fringing and barrier reefs. More photographs of this nature would be welcome. Some of the pictures have lost their original charm and detail through repeated use. This book still serves as a good reference and fulfills its main purpose of providing a well organized textbook in elementary geomorphology.

SIDNEY E. WHITE

A Hadrosaurian Dinosaur from New Jersey; by EDWIN H. COLBERT. Proceedings of the Academy of Natural Sciences of Philadelphia, Vol. C. 1948, pp. 23-37. In this brief paper Doctor Colbert announces the discovery of a Cretaceous dinosaur which he refers to the species *Hadrosaurus minor* described by Professor Marsh in 1870. Our knowledge of the New Jersey hadrosaurs is very meagre for it is based upon several specimens found from time to time in the marl pits as a byproduct of commercial activity, none of which approaches the degree of completeness of the numerous hadrosaurs found in the west. As a consequence any material which may be studied by so competent a paleontologist

as Doctor Colbert has an actual significance far beyond its apparent value as a specimen. The present partial specimen, consisting as it does of thirteen vertebrae, a pubis, ischium, femur, and part of a fibula, adds certain diagnostic characters to our understanding of the animal. Unfortunately, however, no part of the skull was found, which, were it present, would greatly amplify our knowledge of these interesting forms.

The specimen was recovered from a sand pit near Sewell, near Barnsboro, New Jersey, the geological horizon being the Navesink formation, Cretaceous. It is now in the Museum of the Academy.

RICHARD S. LULL

Farm Soils, Their Management and Fertilization; by EDMUND L. WORTHEN. 4th Ed. Pp. xiii, 510; 199 Figures. New York, 1948 (John Wiley and Sons, Inc., $3.20).—The present edition was published seven years after the third edition. It is a book prepared for farmers and others interested primarily with practical soil management problems. The chapter titles are as follows: Selecting the Soil and Planning Its Management, Growing the Crop, Draining and Irrigating Soils, Controlling Soil Erosion, Tilling the Soil, Manuring, Liming, Fertilizing, Replenishing Nitrogen and Supplying Organic Matter, Managing Field Soils, Managing Pasture Soils, Managing Garden, Greenhouse, and Lawn Soils, and Managing Fruit Soils. The chapter on controlling soil erosion is a new one and much useful information is given on this subject. The chapter on Replenishing Nitrogen and Supplying Organic Matter has been revised from the previous edition and new material has been added.

One criticism of the book is that only meager information is given about the soil itself. The book is woefully lacking in information about kinds of soils occurring in the United States and about their development. The information that is given is archaic, and anyone interested in what soils are would have to refer to another book to find out. Knowledge of this kind is important for county agents, agricultural extension workers, and soil conservation technicians use it in their every-day recommendations on soil management.

Little information is contained on the newer kinds of fertilizers produced and especially the newer nitrogen forms which were in use a year or so prior to the publication of this book. Little information is contained on soil structure and ways for managing or improving the physical condition of the soils.

For one who is interested in practical farming this book should prove very useful. Most of the material as well as the pictures has been brought up to date. It is easy to read and understandable. It is recommended to those interested in making a living off of a farm or those interested in managing farms. C. L. W. SWANSON

Soil Physics; by L. D. Baver, 2nd Ed. Pp. xiii, 398; 89 figures. New York, 1948 (John Wiley and Sons, Inc., $4.75).—This expanded and revised edition of Baver's book on soil physics contains 28 more pages than the first edition. The chapter titles remain the same as in the first edition. They are: Introduction, Mechanical Composition of Soils, Physical Characteristics of Soil Colloids, Soil Consistency, Soil Structure, Soil Water, Soil Air, Soil Temperature, Physical Properties of Soils and Tillage, and Physical Properties of Soils in Relation to Runoff and Erosion.

New material has been included on electron micrographs and clay particles, effect of micro-organisms on soil structure, plowing, soil water, and raindrop effects on soil erosion. Addition of this new material makes this book more than ever the leading text book on soil physics.

For those interested in soil moisture relationships this subject is discussed in detail. Soil moisture energy relationship are adequately discussed including the pF concept of soil water.

This book brings together and discusses the relationship existing between structure as it exists in the natural soil profile and structure as we know it in cultivated agricultural soils. Too often the tendency is to treat these two kinds of soils structure separately not relating one to the other.

It is unfortunate that the author did not go into the mineralogical nature of clay in greater detail even though he says it is not the purpose of the book to discuss this matter thoroughly. The reviewer believes that, had he drawn upon the large store of mineralogical information on clays available in the mineralogical literature, his treatment of clays and their relationship to soils would have been improved. Even so, his discussion of soil clays brings together in one place more information about them than is available elsewhere.

For anyone interested in soil physics this is a must book. It is well written and includes a good list of references on the field of soil physics. C. L. W. SWANSON

Human Geography, An Ecological Study of Society; by C. L. White and G. T. Renner. Pp. x, 692; 437 figs. New York, 1948 (Appleton-Century-Crofts Inc., $6.00).—The content of the introductory course in geography is a topic for endless debate. Some hold for rigid earth-science, with little or no human geography. Others urge economic geography, perhaps with a brief earth-science introduction. A third group recommends world regions as the first geographical study. White and Renner follow a fourth tradition, that of "human ecology."

Because each chapter deals first with a natural factor and then with human "adjustments," the book will be poison to those who

eschew even the most dilute environmentalism. Geography, it has been truly said, cannot be defined as a field of knowledge in terms of a particular kind of explanation. But an introductory textbook is not a methodological treatise. The ecological approach, if handled with skill and with candor as to its limitations, may give the beginning student an illuminating introduction to geography which is not necessarily wrong because it is incomplete.

The reviewer would criticize White and Renner for their deviations from the ecological approach rather than their adherence to it. The chapters are interesting and convincing in their descriptions of the habitats and the simpler human adjustments to them. The limitations of the ecological approach become apparent when the complexities of society and politics are reached. Some of the "political adjustments" are not adjustments at all, but merely coincidences. Others are highly debatable, such as the statement that irrigation in the Middle East required absolute despotism (p. 419).

Every man has his home in a climatic region, surrounded by landforms, on some kind of soil, and near surface or underground water. Relatively few men live in, on, or even near important economic mineral deposits. For most men, economic minerals become part of the effective environment only when they are extracted and, in most cases, processed. They are cultural rather than natural factors. For this reason, the strict ecological approach breaks down when minerals are studied and these chapters of White and Renner seem lifted from economic geography. There is no doubt, however, that the book would have been criticized had minerals been ignored or treated only briefly.

Specialists will find a number of errors. We are told, for instance, that coal occurs in veins or sheets (p. 475) and that "Nature intended that the Mediterranean should be an international sea" (p. 201). The controversial Wegener theory of continental drift, Taylor theory of race migration, and organic theory of society are espoused with little or no discussion of alternative views. A conscientious teacher will have to point out overgeneralizations. Nevertheless, the book is readable, as textbooks go, and it may be better for students to read a book that falls short of complete accuracy rather than merely possess one that is accurate but hopelessly dull. Excellent illustrations, clear maps, well-spaced lines, and well-designed pages are additional attractions.

STEPHEN B. JONES

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Published monthly: one volume annually.

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Entered as second-class matter at the Post Office at New Haven, Conn., under the Act of March 8, 1879.

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